N.L. 2016 Project Abstract
For the Period Ending June 30, 2019

PROJECT TITLE: Understanding Bedrock Fracture Flow to Improve Groundwater Quality
PROJECT MANAGER: Anthony C. Runkel
AFFILIATION: Minnesota Geological Survey (University of Minnesota)
MAILING ADDRESS: 2609 Territorial Road
CITY/STATE/ZIP: St Paul, MN, 55114
PHONE: (612) 626-1822
E-MAIL: runke001@umn.edu
WEBSITE: http://www.mngs.umn.edu/
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 04g
APPROPRIATION AMOUNT: $183,000
AMOUNT SPENT: $183,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results
The principle outcome is improved understanding of how groundwater flows in fractured rock, which will lead to more effective remediation of contamination, improved strategies to protect unimpacted groundwater and address water quantity issues. These outcomes are relevant to much of southeastern and northeastern Minnesota where aquifers are dominated by fractured bedrock.

Overall Project Outcome and Results

The goal of this project was to gain an improved understanding of groundwater flow through fractured limestone bedrock by using recently developed techniques. We focused on the Platteville Formation in the Twin Cities Metropolitan area, where the formation is one of the most heavily contaminated bedrock layers in the state. There were two primary activities. One was collection of a variety of geologic and hydrologic information from monitor wells. This was accomplished at two sites near the Mississippi River in Minneapolis; on the campus of the University of Minnesota, and near Minnehaha Falls. We used recently developed techniques that included borehole geophysical testing and instrumentation with multiple pressure and temperature sensors. Two monitor wells at each site were instrumented with sensors. A second activity was detailed mapping of fractures at an exposure of the Platteville Formation at the UMN campus site. Determining how water travels through the Platteville is achieved by combining the results of these two activities.

The project results greatly improved our understanding of how groundwater moves through the Platteville Formation. A key outcome was identification of predictable low permeability layers within the Platteville Formation that can hinder vertical transport of contaminants. The presence of these layers means that conventional techniques for monitoring and remediating contamination plumes would not be as effective as presumed. The results of our project can also be used in groundwater models to improve their accuracy to guide water management engineering. The relevance of our results to how groundwater contamination is characterized and remediated, and to water quantity issues, applies not only to the Platteville Formation, but to all fractured rock aquifers and aquitards in Minnesota. The rigorous techniques such as the inexpensive and efficient methods used in this project can therefore be used to improve water quality across much of Minnesota. A summary report provides greater detail on all the results of this project and their relevance.

Project Results Use and Dissemination
We have presented our results as the project progressed to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges training students who will ultimately become the next generation

of groundwater managers in Minnesota. Our results will continue to be disseminated in this fashion, and in published reports. A summary report with greater detail on all our results is already available.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2016 Work Plan Final Report

Date of Report: October 14, 2019

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2019

PROJECT TITLE: Understanding Bedrock Fracture Flow to Improve Groundwater Quality

Project Manager: Anthony C. Runkel

Organization: Minnesota Geological Survey (University of Minnesota)

Mailing Address: 2609 Territorial Road

City/State/Zip Code: St Paul, MN, 55114

Telephone Number: (612) 626-1822

Email Address: runke001@umn.edu

Web Address: http://www.mngs.umn.edu/

Location: Work will take place in Hennepin County. Counties most directly impacted will be Hennepin, Ramsey, Dakota, Washington, and Anoka. Indirect impact to all of southeastern Minnesota.

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$183,000**
	Amount Spent:	**$183,000**
	Balance:	**$0**

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04g

Appropriation Language:
$183,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota for the Minnesota Geological Survey to use new techniques of borehole testing and rock fracture mapping in the Twin Cities metropolitan area to achieve a better understanding of groundwater flow through fractured bedrock, in order to improve groundwater management. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Understanding bedrock fracture flow to improve groundwater quality

II. PROJECT STATEMENT:
Using new borehole testing and rock fracture mapping techniques we will gain a better understanding of groundwater flow through fractured bedrock in the Twin Cities that will support better management of water quality and quantity. Groundwater flow in bedrock occurs mostly through fractures (cracks in the rock) in a manner that remains difficult to predict, hampering efforts to protect and remediate groundwater. This problem is particularly acute across southeastern Minnesota, including the Twin Cities, where fractured limestone bedrock is a source of baseflow to streams, and also a source of drinking water. Contaminated water from point (e.g. petroleum products and solvents) and non-point (e.g. nitrate) sources in these limestones is well-known. Point-source contamination plumes are a particular problem in the Twin Cities, with a large number of actively monitored and remediated sites, including Superfund sites in Minneapolis, St. Louis Park, Oakdale, and Edina.

The project will focus on the Platteville Formation in the Twin Cities, a fractured limestone, which is one of the most heavily contaminated bedrock layers in the state. It is also hosts a large number of springs, such as Camp Coldwater spring, that discharge to the Mississippi River, and is the bedrock foundation for infrastructure in the urban core. At a site along the Mississippi River in Minneapolis, we will use recently developed techniques of borehole testing and installation of pressure and temperature sensors in five monitor wells, and detailed mapping of fractures at nearby rock exposures. Pressure and temperature measurements collected from the wells will provide us with information on water flow through fractures, and when evaluated in the context of nearby fracture mapping at the rock exposures, will allow us to link hydraulic (water) properties to rock (fracture) properties to provide a greater understanding of fracture flow.

Application of our results will improve the efficiency and effectiveness of remediation and monitoring at a large number of contamination sites across the Twin Cities. The results will also be applicable to water management at construction (tunneling, building foundation, roadwork) sites, and to modeling groundwater-surface water interaction in areas such as the Minnehaha Creek Watershed. The results will provide a better understanding of fracture controlled flow through limestones regionally across southeastern Minnesota, and therefore link to the mapping of these limestones as part of ongoing County Geologic Atlas mapping progam, such as the in-progress Hennepin County Atlas.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 15, 2017: The project is proceeding on schedule and very close to anticipated budget. Working in collaboration with University of Guelph hydrologists we collected information from two monitor wells on the University of Minnesota, Twin Cities campus and successfully instrumented the two holes with temperature and pressure sensors inside of flexible borehole liners, according to our original plan. The only problem encountered was tears in one of the two borehole liners, which were repaired, but possibly may occur again. An unanticipated positive addition to the project was collection of information from similar fractured rock monitor wells elsewhere in Minneapolis, as a result of our collaboration with unpaid project partner Kelton Barr of Braun Intertec.

Project Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Project Status as of January 15, 2018: The project is proceeding on schedule and very close to anticipated budget. Temperature and pressure data have been successfully downloaded from the two instrumented wells. The data from one well is yielding excellent information that is providing insight into groundwater flow. Data from the second well may be compromised by a nearby steam tunnel shaft on the University of Minnesota campus, and we have therefore made arrangements to deploy the instruments in a monitor well at a nearby contamination site managed by the Minnesota Pollution Control Agency. Imaging of fractured bedrock using drone-based photography was successful, and ground-truthing of these images is progressing as planned.

Amendment Request (01/15/2018): A number of minor (~$6000 total) changes have been made to the budget as a result of costs incurred being different from original estimates, and because we are now planning a new task of instrumenting a third monitor well. Costs for two budget items (Professional/Technical Service Contracts and Equipment/Tools/Supplies) for Activity 1 totaled $1326 more than estimated. Capital expenditure for Activity 1 was $5660 less than estimated. Therefore $1326 was moved from capital expenditure to Professional/Technical Service Contracts and Equipment/Tools/Supplies to zero out those balances for Activity 1. The remaining $4334 originally budgeted for capital expenditure, along with $1000 budgeted for equipment shipping for Activity 2, has been combined into an Activity 2 budget item that includes costs for general equipment, shipping of equipment, supplies for sensors and related devises for existing and new well. Finally, $538 in unused funds for travel expenses for Activity 1 were moved to travel expenses for Activity 2. These changes to the equipment and travel budget will allow us the flexibility to cover variable costs incurred in the continued monitoring of one well on the University of Minnesota campus, and to instrument and collect data from the new well at a contamination site in Minneapolis. Amendment Approved by LCCMR 1/17/2018.

Project Status as of July 1, 2018: The project is proceeding on schedule and according to anticipated budget. Temperature and pressure data continue to be successfully downloaded from an instrumented well, yielding excellent information that is providing insight into groundwater flow. We still have plans to deploy similar instruments in a monitor well at a nearby contamination site managed by the Minnesota Pollution Control Agency. Imaging of fractured bedrock using drone-based photography was successful, and ground-truthing of these images is nearly complete. We have presented our data collected thus far, and preliminary results, to groundwater scientists and managers at local (Minnesota) and regional (North Central section of the Geological Society of America) meetings.

Project Status as of January 15, 2019: The project is proceeding on schedule. We now have over two years of data from one instrumented well. Since the last report we have successfully instrumented a second well, and collected several months of data. The field work for fracture characterization is complete, and the data are being processed and interpreted. The data have not been fully processed and interpreted, but appear to show characteristics of groundwater conditions that match up in a predictable fashion to what we have learned about fractures in the outcrop. Together, these results are providing the first detailed insight into how fracture patterns dictate variable degrees of groundwater flow connectivity in the Platteville Formation. These results will also apply to many other hydrogeologic units in Minnesota. This has important implications for predicting contaminant transport and devising groundwater remediation, monitoring strategies, and modeling. We have presented our results to water resources groups at the Minnesota Department of Health, the regional branch of the American Institute for Professional Geologists, and to local colleges. As for budget, we have spent more in salaries than predicted, but will continue to fully accomplish all of our tasks and goals, using Minnesota Geological Survey general funds.

Project Status as of June 17, 2019: We have now collected information from five wells, three on the University of Minnesota campus and two near Minnehaha Falls. This greatly exceeds the number of wells and geographic scope of the originally proposed work. The data have not been fully processed and interpreted, but appear to show characteristics of groundwater conditions that match up in a predictable fashion to what we have learned about fractures in the outcrop. Together, these results are providing the first detailed insight into how fracture patterns dictate variable degrees of groundwater flow connectivity in the Platteville Formation. These results will also apply to many other hydrogeologic units in Minnesota. This has important implications for predicting contaminant transport and devising groundwater remediation, monitoring strategies, and modeling. We have presented our results to water resources groups at the Minnesota Department of Health, the regional branch of the American Institute for Professional Geologists, and to local colleges. As for budget, we have spent more in salaries than predicted, but will continue to fully accomplish all of our tasks and goals, using Minnesota Geological Survey general funds.

AMENDMENT REQUEST June 17, 2019
We are requesting funds be shifted from the Supplies (Equipment/Tools/Supplies) and Travel budget lines to personnel.

- the supplies budget for Activity 2 would be reduced by $603 to a revised budget of $4731
- The travel budget for Activity 2 would be reduced by $377 to a revised budget of $968
- The personnel budget for Activity 2 would increase by $980 to a revised budget of $17,745

These changes are being requested because we spent slightly less money than predicted for supplies and travel. Meanwhile, we have exceeded our predicted personnel costs for Activity 2. Personnel costs exceeded our predication because we have been fortunate enough to locate and acquire permission to instrument and collect data from three additional monitor wells, with data collection continuing. This will greatly enhance our overall project results beyond our expectations. But it also required personnel effort beyond our predictions. The Minnesota Geological Survey general budget will be covering all excess salary incurred beyond the $980 made available through this amendment request.

We are also proposing a change to XI. REPORTING REQUIREMENTS, asking for a no-cost extension to the August 15, 2019 deadline for when we submit our final report and associated products. We propose to extend this date two months, to October 15, 2019. This change is being requested because we have exceeded the number of wells we originally proposed to instrument, and also exceeded the duration of the instrumentation and data collection. Instead of monitoring two wells for two years, we have now monitored five wells, and continue to collect data from some of them. This significantly improves our overall project results, and broadens the geographic scope of our investigation to include the Minnehaha Falls area. Although the salary overruns incurred are being covered by the MGS general budget, this additional data does require additional time for synthesis and writing a report of our results with associated products.

Amendment Approved by LCCMR 6/26/2019.

Overall Project Outcomes and Results: The goal in this project was to gain an improved understanding of groundwater flow through fractured limestone bedrock by using recently developed techniques. We focused on the Platteville Formation in the Twin Cities Metropolitan area, where the formation is one of the most heavily contaminated bedrock layers in the state. There were two primary activities. One was collection of a variety of geologic and hydrologic information from monitor wells. This was accomplished at two sites near the Mississippi River in Minneapolis; on the campus of the University of Minnesota, and near Minnehaha Falls. We used recently developed techniques that included borehole geophysical testing and instrumentation with multiple pressure and temperature sensors. Two monitor wells at each site were instrumented with sensors. A second activity was detailed mapping of fractures at an exposure of the Platteville Formation at the UMN campus site. Determining how water travels through the Platteville is achieved by combining the results of these two activities.

The project results greatly improved our understanding of how groundwater moves through the Platteville Formation. A key outcome was identification of predictable low permeability layers within the Platteville Formation that can hinder vertical transport of contaminants. The presence of these layers means that conventional techniques for monitoring and remediating contamination plumes would not be as effective as presumed. The results of our project can also be used in groundwater models to improve their accuracy to guide water management engineering. The relevance of our results to how groundwater contamination is characterized and remediated, and to water quantity issues, applies not only to the Platteville Formation, but to all fractured rock aquifers and aquitards in Minnesota. The rigorous techniques such as the inexpensive and efficient methods used in this project can therefore be used to improve water quality across much of Minnesota. A summary report provides greater detail on all the results of this project and their relevance.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Monitor well testing and installation of pressure and temperature sensors.
Description: We will use borehole geophysical and video tools to identify and measure fractures, and measure water flow, in two monitor wells on University of Minnesota campus. That information will be used to design and install flexible borehole liners (1 each well) and sensors (15 each well) that will measure pressure and

temperature every five seconds. This work will be conducted by Minnesota Geological Survey scientists, working with the Centre for Applied Groundwater Research, University of Guelph, Ontario, the latter under a Professional/Technical Service contract.

Summary Budget Information for Activity 1:

ENRTF Budget: $110,800
Amount Spent: $ 110,800
Balance: $ 0

Outcome	Completion Date
1. Depiction of fracture patterns in the two monitor wells, that can be compared with fracture patterns that we characterize from outcrops (Activity 3)	February 15, 2017
2. Measurements of groundwater flow through fractures in the two monitor wells	February 15, 2017
3. Borehole liners and sensors installed in the two wells will provide temperature and pressure data for a period of two years (Activity 2)	February 15, 2017

Activity Status as of January 15, 2017: Working in collaboration with hydrologists from the University of Guelph, Minnesota Geological Survey staff measured fractures, water flow and other properties in the two monitor wells on the University of Minnesota Twin Cities campus in August, 2016. We purchased two flexible borehole liners, and a total of 27 sensors and successfully installed them in the wells in late August and early September. The cost of the liners was $661.66 more than budgeted due to the inclusion of venting tubes that were deemed necessary to facilitate liner insertion. This negative balance will be addressed in a future amendment request.

An unanticipated issue was that the flexible liner in one monitor well developed two small leaks (tears in the liner), which were repaired, and the liner successfully reinstalled. As we continue our project, extracting and reinstalling the liners, it is possible that other leaks will develop, which may require purchase of new liners. If this is necessary we will request an amendment to our budget and cover the cost from other categories. The status overall is very close to what we anticipated.

The holes are now successfully instrumented with sensors that are continuously collecting temperature and pressure data, and we will be downloading those data in February or March, as part of Activity 2, when outside temperatures are warmer.

An unanticipated positive addition to the project was collection of information from similar fractured rock monitor wells elsewhere in Minneapolis, as a result of our collaboration with unpaid project partner Kelton Barr of Braun Intertec.

Activity Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Activity Status as of January 15, 2018: Most of Activity 1 was completed at the time of the previous status report, as described above. Remaining activities included interpretation of data acquired from the two monitor wells and adjustments made to the sensor installations.

Activity Status as of July 1, 2018: Completed

Activity Status as of January 15, 2019: Completed

Activity Status as of June 17, 2019: Completed

Final Report Summary: We instrumented five monitor wells with sensors that continuously collected temperature and pressure data. Four of the five monitor wells yielded extremely useful information. This doubles the number of wells (two) we intended to collect information from. The additional monitor wells were added as a result of our collaboration with unpaid project partner Kelton Barr of Braun Intertec. This greatly enhanced the value of our project because the additional information led to improved predictability of groundwater flow through the Platteville Formation across a larger area of the Twin Cities Metro, as described for Activity 4.

ACTIVITY 2: Collect groundwater pressure and temperature data from monitor wells for 3 years
Description: Scientists from the Minnesota Geological Survey will extract sensors from wells at approximately 6 month intervals to download temperature and pressure data, followed by re-insertion of sensors for additional data collection. As of December 28, 2017 we now have plans to instrument a third well, at a Minneapolis contamination site.

Summary Budget Information for Activity 2:

ENRTF Budget:	**$23,444**
Amount Spent:	**$ 23,444**
Balance:	**$ 0**

Outcome	**Completion Date**
1. Acquisition of two years of continuous (five second intervals) data showing temperature and pressure variability that provide an understanding of groundwater flow conditions	November 1, 2018

Activity Status as of January 15, 2017: Sensors are successfully installed (Activity 1), and we anticipate our first download of data to occur in February or March depending on weather conditions.

Activity Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Activity Status as of January 15, 2018: We have now downloaded data from the two monitor wells multiple times. The installations are successfully providing temperature and pressure data as planned. Data have been processed, calibrated, and disseminated to collaborators. The data from one of the two monitor wells reveal very useful insights into groundwater flow conditions. The data from the second of two monitor wells appear to be far less useful, because of the unanticipated presence of a leaky underground shaft close to the well. We have therefore made plans to install and collect data from a third monitor well, at a contamination site in Minneapolis, working in collaboration with the Minnesota Pollution Control Agency and Braun Intertec. The minor changes to our budget as part of our Amendment request are intended to give us more flexibility to install and collect data from this third monitor well.

Activity Status as of July 1, 2018: We have now downloaded data from the two monitor wells multiple times. The installations are successfully providing temperature and pressure data as planned. Data have been processed, calibrated, and disseminated to collaborators. The data from one of the two monitor wells continues to provide us with very useful insights into groundwater flow conditions. The data from the second of two monitor wells appear to be far less useful, because of the unanticipated presence of a leaky underground shaft close to the well. We have therefore discontinued collection of data from that well, and made plans to install and collect data from a third monitor well, at a contamination site in Minneapolis, working in collaboration with the Minnesota Pollution Control Agency and Braun Intertec.

Activity Status as of January 15, 2019: We have now downloaded data from three monitor wells multiple times. Data have been processed, calibrated, and disseminated to collaborators. The most recently instrumented of these wells is for the first time providing us with information on groundwater conditions in a more highly fractured setting, giving us a broader perspective on how flow conditions change from place to place, when the geologic setting changes. The gives our results broader application to groundwater contamination problems. Our results have been promising enough, especially with the recently instrumented well, that we continue to monitor and collect data, which may continue beyond the formal duration of this project, using alternate sources of funding.

Activity Status as of June 17, 2019: We have now downloaded data from five monitor wells multiple times. Data from three of the wells have been processed, calibrated, and disseminated to collaborators. More recently we were able to take advantage of two wells drilled by Metropolitan Council near Minnehaha Falls, which gives us a broader perspective on how flow conditions change from place to place, when the geologic setting changes. The gives our results broader application to groundwater contamination problems, and will also have relevance to ongoing concerns about Camp Coldwater Spring near Minnehaha Falls. Our results have been promising enough, especially with these recently instrumented wells, that we continue to monitor and collect data, which will continue beyond the formal duration of this project, using alternate sources (MGS general budget) of funding.

Final Report Summary: We acquired useful data from four monitor wells multiple times over a period of nearly three years. By adding a second study site with two wells, beyond the scope of the original project, we were able to gain a broader perspective on how flow conditions change from place to place, when the geologic setting changes. The gives our results broader application to groundwater contamination problems, and will also have relevance to ongoing concerns about Camp Coldwater Spring near Minnehaha Falls and to water level issues within the Minnehaha Creek Watershed. Our results were promising enough, especially with these added monitor wells, that we continued to monitor and collect data beyond the formal duration of this project, using alternate sources (MGS general budget) of funding.

ACTIVITY 3: Map fractures in bedrock along Mississippi River near the tested monitor wells
Description: Fractures (cracks) in the limestone of the Platteville Formation will be mapped by photo-based trace mapping of exposures along east bank of Mississippi River, about 500 yards from monitor wells tested as part of Activity 1. This process includes high-resolution, seamless photograph collected by a camera mounted on a drone, near Washington Avenue bridge. Fractures shown on the photograph will be traced on the photograph electronically in the office, and then adjusted and measured in the field, on the outcropping. The final product with be a depiction of the natural fractures system in the Platteville Formation.

Summary Budget Information for Activity 3:

ENRTF Budget:	**$ 18,450**
Amount Spent:	**$ 18,450**
Balance:	**$ 0**

Outcome	**Completion Date**
1. Documentation of the fracture patterns that control groundwater flow	November 1, 2018

Activity Status as of January 15, 2017: No activity. Planned to begin in March or April, 2017

Activity Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Activity Status as of January 15, 2018: Outcrop photographed and videoed using drone. Photos and videos processed and compiled into 3 dimensional images. Computer and field-based fracture tracing and measuring roughly half complete. Progress is as planned.

Activity Status as of July 1, 2018: Outcrop photographed and videoed using drone. Photos and videos processed and compiled into 3 dimensional images. Computer and field-based fracture tracing and measuring is nearly complete, with field work to be entirely finished this fall (2018). Progress is as planned.

Activity Status as of January 15, 2019: Completed

Activity Status as of June 17, 2019: Completed

Final Report Summary: Outcrop photographed and videoed using drone. Photos and videos processed and compiled into 3 dimensional images. Computer and field-based fracture tracing and measuring was completed. Results demonstrated that the Platteville Formation contains seven layers where fractures are not continuous. This is important because those layers can hinder vertical transport of contamination to deeper levels in the groundwater system. The position of those layers is compared to the information we collected from monitor wells, to determine how groundwater flows in the Platteville Formation, as part of Activity 4.

ACTIVITY 4: Synthesize information, disseminate results to groundwater managers.

Description: Compile and interpret pressure and temperature data collected from the five monitor wells, to understand how water flows through fractures. Compare and evaluate these results to fracture patterns mapped at nearby rock exposure to link together fracture patterns with water flow. Produce reports and presentations summarizing the results, which will be disseminated to organizations that have a role in managing groundwater quality and quantity, such as MPCA, DNR, County environmental managers, and environmental consulting industry.

Summary Budget Information for Activity 4:

ENRTF Budget:	**$ 30,306**
Amount Spent:	**$ 30,306**
Balance:	**$ 0**

Outcome	**Completion Date**
1. Peer reviewed report(s) and public presentations of results that explain how fractures control groundwater flow, which will lead to more effective remediation of contamination sites, and improve management strategies to better protect fractured rock aquifers from further degradation	July 1, 2019

Activity Status as of January 15, 2017: No activity.

Activity Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Activity Status as of January 15, 2018: Data downloaded from two monitor wells has been synthesized and interpreted. Results thus far from fracture tracing have been interpreted and compared to pressure and temperature data from monitor wells.

Activity Status as of July 1, 2018: Downloaded data continues to be synthesized and interpreted. Results thus far from fracture tracing have been interpreted and compared to this pressure and temperature data.

Activity Status as of January 15, 2019: We have begun to process data from the monitor wells and fractured outcrop into formats where they can be more readily compared to one another, fully interpreted, and disseminated to groups with interest in groundwater contamination. Preliminary interpretation appears to show great promise in linking fracture patterns to the groundwater data we have collected from monitor wells. Together, these results are providing the first detailed insight into how fracture patterns dictate variable degrees of flow connectivity in the Platteville Formation. These results will also apply to many other hydrogeologic units in Minnesota. This has important implications for predicting contaminant transport and devising groundwater remediation and monitoring strategies. We have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

Activity Status as of June 17, 2019: We continue to process data from the monitor wells and fractured outcrop into formats where they can be more readily compared to one another, fully interpreted, and disseminated to groups with interest in groundwater contamination. Preliminary interpretation appears to show great promise in linking fracture patterns to the groundwater data we have collected from monitor wells. Together, these results are providing the first detailed insight into how fracture patterns dictate variable degrees of flow connectivity in the Platteville Formation. These results will also apply to many other hydrogeologic units in Minnesota. This has important implications for predicting contaminant transport and devising groundwater remediation and monitoring strategies. We have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

Final Report Summary: A key outcome was identification of predictable low permeability layers within the Platteville Formation that can hinder vertical transport of contaminants. The presence of these layers means that conventional techniques for monitoring and remediating contamination plumes are not as effective as presumed. Other results of our project such as the three dimensional depiction of fractures, and the relative differences in vertical connectivity across the Platteville Formation can be used in groundwater models to improve their accuracy. These models provide guidance for water management engineering inherent to many of the construction projects in central TCMA, and for groundwater-surface water modelling, such as within the Minnehaha Creek Watershed. The relevance of our results to how groundwater contamination is characterized and remediated, and for improving groundwater models, applies not only to the Platteville Formation, but to all fractured rock aquifers and aquitards in Minnesota. We therefore encourage greater application of more rigorous techniques such as the inexpensive and efficient methods used in this project. We have presented our results as the project progressed to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

V. DISSEMINATION:

Description: We will disseminate results to organizations that have a role in managing groundwater quality and quantity, such as MPCA, MNDNR, County environmental managers, and environmental consulting industry. Dissemination will include presentations at meetings such as the Minnesota Ground Water Association, and begin before the project ends, as we progressively acquire data. At the conclusion of the project, the results will appear in published, peer-reviewed report(s), that are routinely disseminated widely by the Minnesota Geological Survey (MGS), including through our website at http://www.mngs.umn.edu/. MGS reports also include links to all raw data that support the conclusions of the report. Results are also likely to be of sufficient interest and applicability to be published in one or more national or international journals.

Status as of January 15, 2017: No activity

Status as of July 1, 2017: No activity

Status as of January 15, 2018: No activity

Status as of July 1, 2018: We have started to compile data into illustrations for our anticipated report(s). Meanwhile, we have presented our data collected thus far, and preliminary results, to groundwater scientists and managers at local (Minnesota) and regional (North Central section of the Geological Society of America) meetings.

Status as of January 15, 2019: Since the previous report, we have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

Status as of June 17, 2019: Since the previous report, we have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

Final Report Summary:

We have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, the regional (North Central section of the Geological Society of America) meetings, and to local colleges. Our technical report (submitted as an accompanying document) will be published by the Minnesota Geological Survey and disseminated through our website at http://www.mngs.umn.edu/. We will also continue to present the results to consultants and government agencies involved with groundwater quality and quantity issues.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$82,703	1 MGS senior scientist for project management, borehole equipment installation, fracture characterization, and synthesis of results; 16.6% time per year for 3 years, 74% salary, 26% benefits ($45,438); 3 MGS staff for assistance with borehole equipment installation, fracture characterization, and synthesis of results, as follows: 1 MGS senior scientist 8.3% time per year for 3 years, 74% salary, 26% benefits ($21,403); 1 scientist MGS 4.2% time per year for 3 years, 74% salary, 26% benefits ($8,202); 1 assistant scientist MGS 4.2% time per year for 3 years, 74% salary, 26% benefits ($6,680)
Professional/Technical/Service Contracts:	$41464	1 contract with Centre for Applied Groundwater Research (CAGR) , University of Guelph, Ontario: Acquisition of borehole data from two monitor wells that will provide recognition of rock fractures in the wells, and where and in what direction natural groundwater flow occurs. Includes directional temperature logs (CAGR is sole source provider), acoustic and optical televiewer logs, and full waveform sonic logs. Design and installation of a borehole liner and 15 sensors (a technique developed and deployed only by CAGR) in each of two monitor wells (total 2 borehole liners and 30 sensor arrays designed and installed) ($40,000); 1 contract for drone-based photography to image fractured rock along Mississippi River at University of Minnesota, provider TBD ($800)
Equipment/Tools/Supplies:	$8475	Borehole liners to be installed in two monitor wells. FLUTe brand flexible liners, Total of 2

		liners @ $1541 ea ($3082). Shipping of equipment ("Green Machine") necessary to extract and reinsert borehole liner ($1000)
Capital Expenditures over $5,000:	$49,390	Data logger sensors that measure pressure and temperature (to be installed in two boreholes): Total 30 sensors @ $1827.50 ea , plus shipping @ $225 ($55,050)
Fee Title Acquisition:	$	
Easement Acquisition:	$	
Professional Services for Acquisition:	$	
Printing:	$	
Travel Expenses in MN:	$968	Truck rental for monitor well liner installation, retrieval, re-installation (to retrieve data 4 times during course of project) (rental, 5 weeks @ $269/week) ($1345)
Other:	$	
TOTAL ENRTF BUDGET:	**$183,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: Thirty data logger sensors that measure pressure and temperature to be installed in two boreholes will be purchased and will be continue to be used by the Minnesota Geological Survey for the life of these sensors for similar projects and purposes. If the instrument is sold prior to its useful life, proceeds from the sale will be paid back to the Environment and Natural Resources Trust Fund.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 1.0 FTE

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 0.2 FTE

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
	$	$	
State			
University of Minnesota	$95,486	$95,486	In-kind Services To Be Applied To Project During Project Period: The University of Minnesota's Facilities and Administrative rate is 52% of modified total direct costs (total direct less graduate student fringe, capital equipment, subawards over $25,000 and on-site facilities rental). The amount, if F&A expenses would have been allowed on this project, would be $95,486
TOTAL OTHER FUNDS:	**$95486**	**$95,486**	

VII. PROJECT STRATEGY:

A. Project Partners:

Project Partners Receiving Funds:

- **Centre for Applied Groundwater Research** , University of Guelph, Ontario, led by Dr. Beth Parker. $40,000 for geophysical testing and installation of pressure and temperature sensors as a contracted collaboration. This Centre is uniquely capable of acquiring temperature profiles that measure flow direction through fractures in monitor wells, and in installation of the nested pressure and temperature sensors, a procedure developed by their group. The information acquired from these procedures is key to understanding flow through fractures in the two monitor wells we are testing on the University of Minnesota campus. Contribution to interpretation of final results and publication during final year of project will be an unpaid contribution.

Project Partners Not Receiving Funds:

- **Braun Intertec,** Bloomington, Minnesota. Kelton Barr, Principal Hydrogeologist, providing unpaid consultation at all stages of the investigation. Mr. Barr has over 40 years of experience remediating fractured limestone contamination sites in the Twin Cities.

B. Project Impact and Long-term Strategy:

Application of our results will improve the efficiency and effectiveness of remediation and monitoring at a large number of contamination sites across the Twin Cities. The results will also be applicable to water management at construction (tunneling, building foundation, roadwork) sites, and to modeling groundwater-surface water interaction in areas such as the Minnehaha Creek Watershed. The results will provide a better understanding of fracture controlled flow through limestones regionally across southeastern Minnesota, and therefore link to the mapping of these limestones as part of ongoing County Geologic Atlas mapping progam, such as the in-progress Hennepin County Atlas. The borehole equipment purchased for this project, and the investigative methods, can be subsequently deployed in both wells and springs at other sites in southeastern Minnesota.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
Proposed project builds on over 5 years of research by MGS staff on fractured rock groundwater flow in the Platteville Formation, funded through Minnesota Geological Survey base funding, and a 2010 Metropolitan Council grant.	~July 1, 2010-July 1, 2015	$60,000
ENTRF funded a 2010 project "Investigation of the hydrologic properties of the St. Lawrence Formation" (M.L. 2010, Chp. 362, Sec. 2, Subd. 3a). The results of that investigation have led to the development of techniques and concepts that we will apply to this proposed project.	July 1, 2010-June 30, 2013	$307,000

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS:

A. Parcel List: N/A

B. Acquisition/Restoration Information: N/A

IX. VISUAL COMPONENT or MAP(S): See attached visual component

X. RESEARCH ADDENDUM: N/A

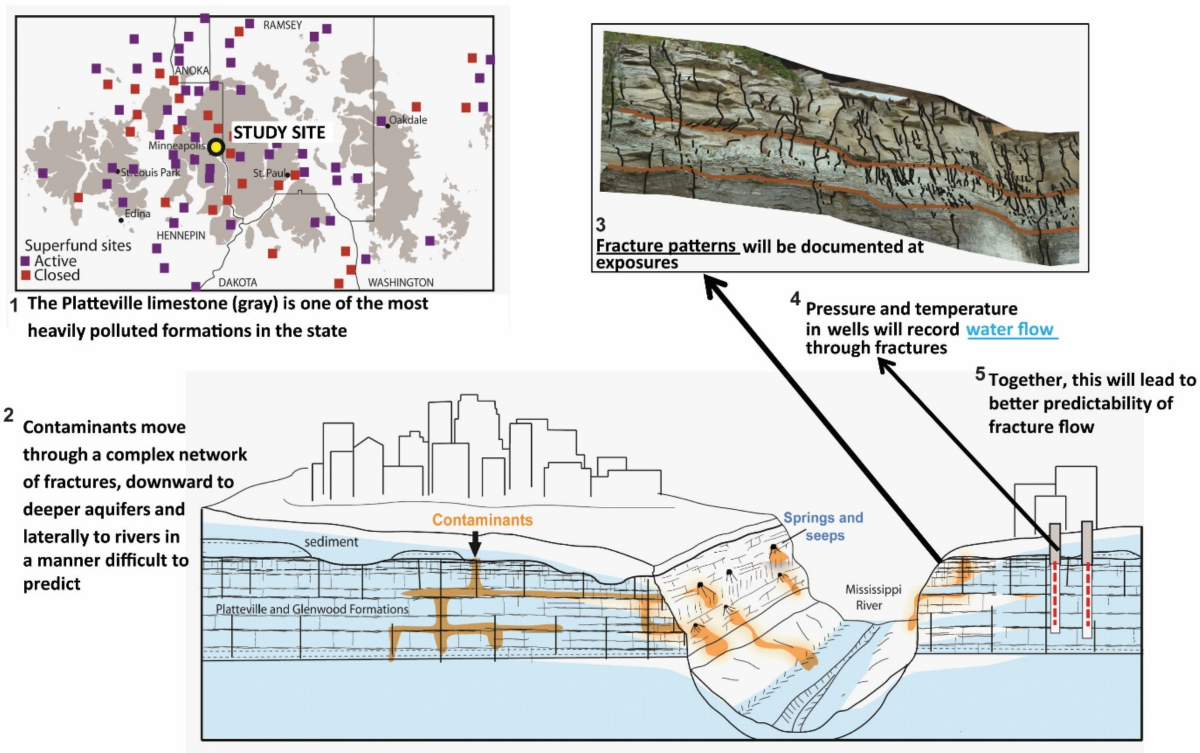
XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than January 15, 2017, July 1, 2017, January 15, 2018, July 1, 2018, January 15, 2019. A final report and associated products will be submitted between June 30 and October 15, 2019.

Understanding Bedrock Fracture Flow to Improve Groundwater Quality

Environment and Natural Resources Trust Fund (ENTRF) (Proposal ID:049-B)

Anthony Runkel, Minnesota Geological Survey



UNIVERSITY OF MINNESOTA

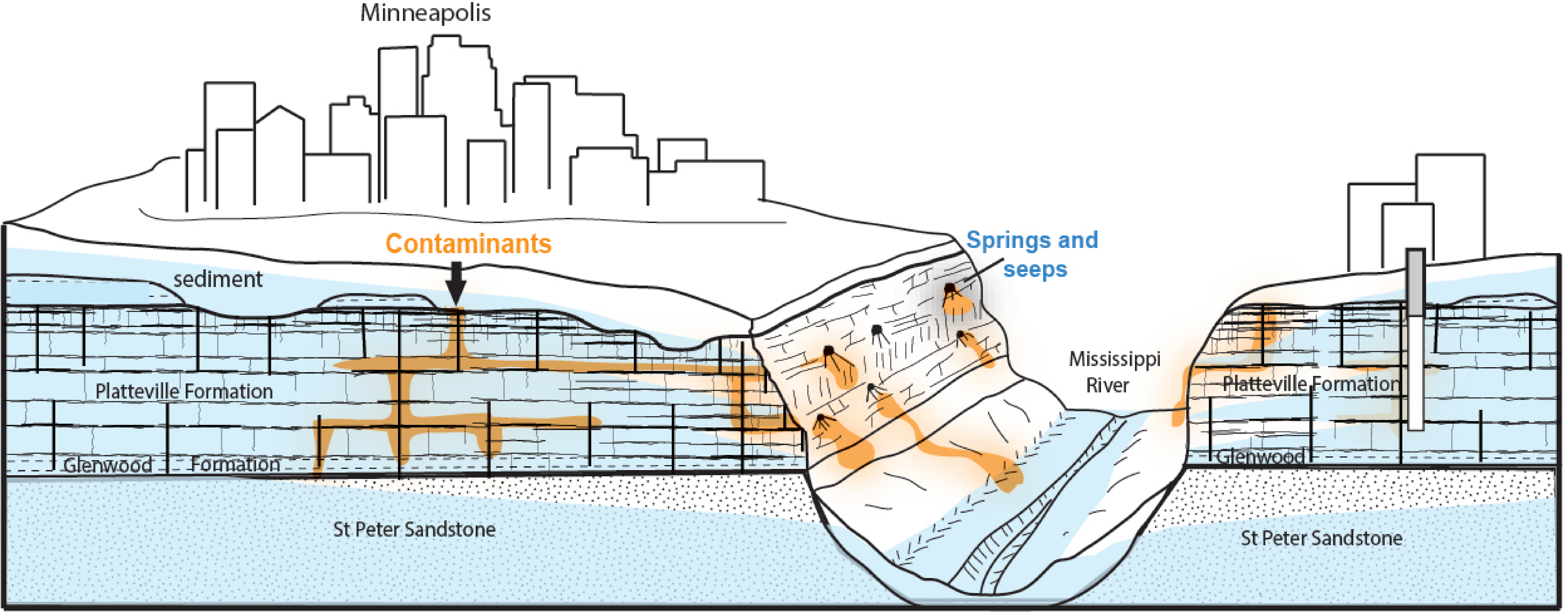
Depiction of the fractured limestone and contamination plumes beneath the Twin Cities

Final Attachment A (Budget Sheet) Budget detail for M.L. 2016 Environment and Natural Resources Trust Fund Projects

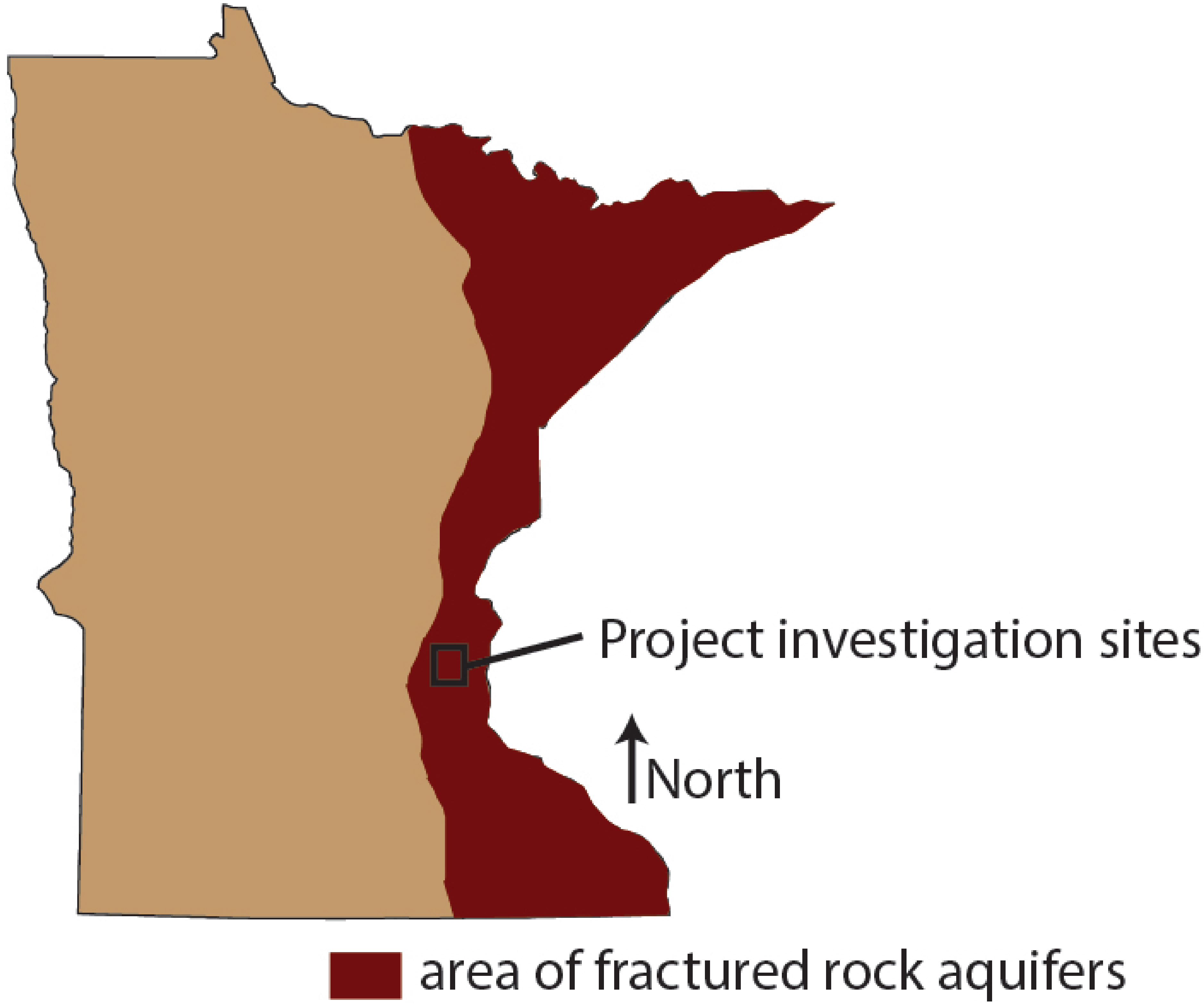
Project Title: Understanding Bedrock Fracture Flow to Improve Groundwater Quality
Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04g
Project Manager: Anthony C. Runkel
Organization: Minnesota Geological Survey (University of Minnesota)
M.L. 2016 ENRTF Appropriation: $ 183,000
Project Length and Completion Date: 3 years, June 30, 2019
Date of Report: October 14, 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget 01/15/2018	Amount Spent	Activity 1 Balance	Revised Activity 2 Budget 06/17/2019	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	Activity 4 Budget	Amount Spent	Activity 4 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM							**Map fractures in bedrock along Mississippi River near the tested monitor wells**			**Synthesize information, disseminate results to groundwater managers.**				
Personnel (Wages and Benefits)	$17,002	$17,002	$0	$17,745	$17,745	$0	$17,650	$17,650	$0	$30,306	$30,306	$0	$82,703	$0
1 senior scientist, Project Manager, MGS: $45,438 (16.6% time per year for 3 years, 74% salary, 26% benefits)						$0								
1 senior scientist, MGS: $21,403 (8.3% time per year for 3 years, 74% salary, 26% benefits)						$0								
1 scientist MGS: $8202 (4.2% time per year for 3 years, 74% salary, 26% benefits)						$0								
1 assistant scientist MGS: $6680 (4.2% time per year for 3 years, 74% salary, 26% benefits)						$0								
Professional/Technical/Service Contracts						$0								
Photography of fractured bedrock along east bank of Mississippi river at U of Minnesota campus, using camera mounted on drone.						$0	$800	$800	$0				$800	$0
Centre for Applied Groundwater Research (CAGR), University of Guelph, Ontario: Acquisition of borehole data from two monitor wells that will provide recognition of rock fractures in the wells, and where and in what direction natural groundwater flow occurs. Includes directional temperature logs (CAGR is sole source provider), acoustic and optical televiewer logs, and full waveform sonic logs. Design and installation of a borehole liner and 15 sensors (a technique developed and deployed only by CAGR) in each of two monitor wells (total 2 borehole liners and 30 sensor arrays	$40,664	$40,664	$0			$0							$40,664	$0
Equipment/Tools/Supplies						$0								
Borehole liners to be installed in two monitor wells. FLUTe brand flexible liners, Total of 2 liners @ $1541 ea	$3,744	$3,744	$0			$0							$3,744	$0
Shipping of equipment ("Green Machine") necessary to extract and reinsert borehole liner ($1000)					$0	$0							$0	$0
General equipment, shipping of equipment, supplies for sensors and related devices for existing and new well.				$4,731	$4,731	$0							$4,731	$0
Capital Expenditures Over $5,000						$0								
Data logger sensors that measure pressure and temperature (to be installed in two boreholes): Total 30 sensors @ $1827.50 ea. plus $225 shipping ($55,050)	$49,390	$49,390	$0			$0							$49,390	$0
Travel expenses in Minnesota						$0								
Equipment rental (truck) for monitor well liner installation, retrieval, re-installation (to retrieve data 4 times during course of project) (truck rental, 5 weeks @ $269/week ; total $1345)	$0	$0	$0	$968	$968	$0							$968	$0
Describe the expense—one row per type/category. Add rows as needed. Be specific.														
COLUMN TOTAL	**$110,800**	**$110,800**	**$0**	**$23,444**	**$23,444**	**$0**	**$18,450**	**$18,450**	**$0**	**$30,306**	**$30,306**	**$0**	**$183,000**	**$0**

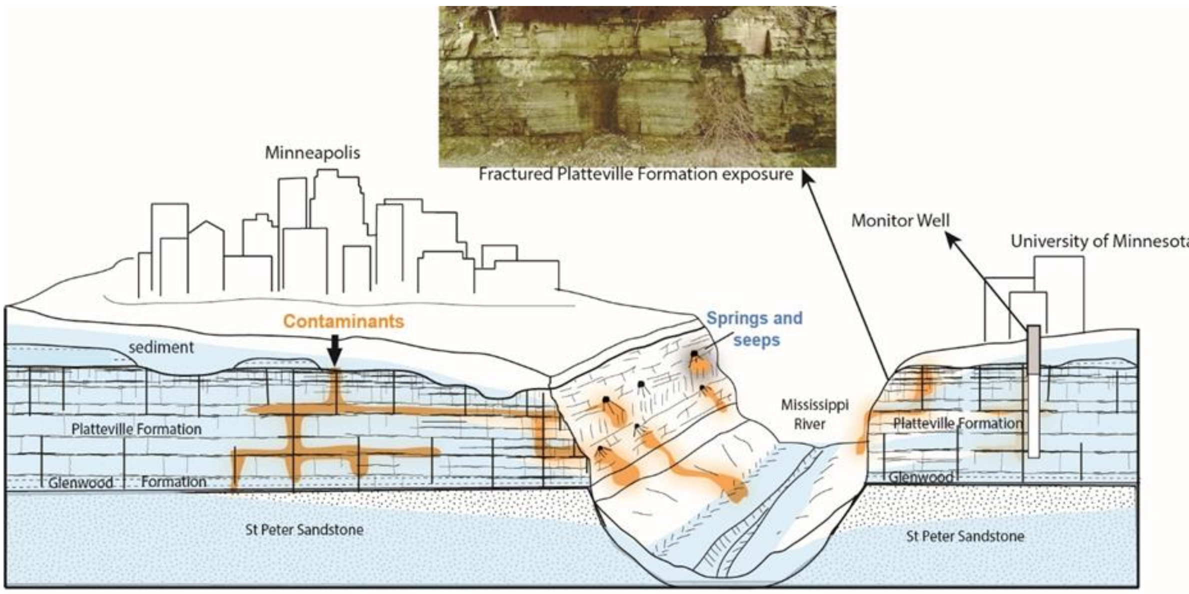
Understanding Bedrock Fracture Flow to Improve Groundwater Quality



GROUNDWATER CONTAMINATION IN FRACTURED ROCK



Understanding Bedrock Fracture Flow to Improve Groundwater Quality



10/13/2019

Report summarizing results of M.L. Chp. 186, Sec. 2, Subd. 04g, Understanding Bedrock Fracture Flow to Improve Groundwater Quality"

Funded by the Minnesota Environmental and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

Anthony Runkel, Julia Steenberg, Andrew Retzler, Robert Tipping

Minnesota Geological Survey

UNIVERSITY OF MINNESOTA

EXECUTIVE SUMMARY

The goal in this project was to gain an improved understanding of groundwater flow through fractured limestone bedrock by using recently developed techniques. We focused on the Platteville Formation in the Twin Cities Metropolitan area, where the formation is one of the most heavily contaminated bedrock layers in the state. There were two primary activities. One was collection of a variety of geologic and hydrologic information from monitor wells. This was accomplished at two sites near the Mississippi River in Minneapolis; on the campus of the University of Minnesota, and near Minnehaha Falls. We used recently developed techniques that included borehole geophysical testing and instrumentation with multiple pressure and temperature sensors. Two monitor wells at each site were instrumented with sensors. A second activity was detailed mapping of fractures at an exposure of the Platteville Formation at the UMN campus site. Determining how water travels through the Platteville is achieved by combining the results of these two activities.

The project results greatly improved our understanding of how groundwater moves through the Platteville Formation. A key outcome was identification of predictable low permeability layers within the Platteville Formation that can hinder vertical transport of contaminants. The presence of these layers means that conventional techniques for monitoring and remediating contamination plumes would not be as effective as presumed. The relevance of our results to how groundwater contamination is characterized and remediated apply not only to the Platteville Formation, but to all fractured rock aquifers and aquitards in Minnesota. We therefore encourage greater application of more rigorous techniques such as the inexpensive and efficient methods used in this project.

INTRODUCTION

Much of the most severe groundwater contamination in Minnesota is in fractured bedrock. The largest urban areas, such as Rochester, Duluth, and the Twin Cities Metropolitan area (TCMA), have numerous point-source contamination plumes in fractured bedrock. More widespread contamination from nonpoint sources, such as high levels of nitrate, is also well-documented in fractured bedrock across much of southeastern Minnesota (Runkel et al., 2013).

Predicting how groundwater flows through fractured rock is one of the most challenging problems in the field of hydrogeology. It is particularly difficult to achieve in aquitards (Bradbury et al. 2006), which are the low permeability rock layers that protect deeper groundwater. Until recently, in-situ methods for testing depth-discrete properties in bedrock aquitards were not well developed, especially the acquisition of data that provides insight into flow through vertical fractures, which are the key pathway for contaminant transport to deeper levels. This has hampered efforts to protect and remediate groundwater.

Our goal in this investigation was to gain an improved understanding of groundwater flow through a fractured limestone aquitard by using recently developed techniques. The project focused on the Platteville Formation, which is an aquitard in the TCMA. It also hosts a large number of springs that discharge to the Mississippi River, and is the bedrock foundation for infrastructure in the urban core (Fig.1). The Platteville is also one of the most heavily contaminated bedrock layers in the state. Point-source contamination plumes are a particular problem in the TCMA, with a large number of actively monitored and remediated sites, including Superfund sites in Minneapolis, St. Louis Park, Oakdale, and Edina (Fig. 2).

At two sites near the Mississippi River in Minneapolis, we collected high resolution pressure and temperature data from monitor wells, along with a detailed map of fractures at a nearby rock exposure (Figs. 1, 2). Borehole geophysical tools were used to measure flow and other characteristics of the groundwater in each of the monitor wells. The chemistry of the groundwater was also analyzed for some monitor wells. Collectively, this information was used to achieve a greater understanding of flow through fractures in the Platteville Formation, and in particular which parts of the formation hinder vertical flow.

Results of this project can be used to more effectively remediate contamination sites and improve management strategies to protect fractured rock aquitards and aquifers from further degradation. In addition to contamination issues, the results provide guidance for water management engineering inherent to many of the construction projects in central TCMA, and for groundwater-surface water modelling, such as within the Minnehaha Creek Watershed. The results are also more broadly applicable across greater southeastern Minnesota, where fractured bedrock is the primary source of baseflow to streams, and the major source of potable water.

GENERAL GEOLOGIC AND HYDROLOGIC SETTING

The Upper Ordovician Platteville Formation has a patchy distribution in the central part of the TCMA (Fig. 2). Across much of the area it is shallowly buried (<30 m, 100 ft) by unconsolidated Quaternary sediment, and occupies a position near the top of the Paleozoic bedrock sequence of the Twin Cities basin, a broad regional depression developed in the northernmost extent of Paleozoic bedrock in the Upper Mississippi Valley region (Mossler 1972). The stratigraphic and hydrogeologic properties of the Platteville and adjacent bedrock units have been characterized in a number of publications, as well as unpublished consultant reports. Those results are summarized in this section, with greater detail available in Anderson et al. (2011), Tipping et al. (2011), and Runkel et al. (2003, 2015).

The Platteville ranges from about 26 to 29 feet thick and is subdivided into four members; from bottom to top they are the Pecatonica, Mifflin, Hidden Falls and Magnolia (Mossler 1985, 2008) (Fig. 3). These are distinguished mainly by lithology and bedding style and correspond to major depositional facies. The Pecatonica Member lies directly on top of the Glenwood shale, and is a burrowed, reworked, fossiliferous dolostone only 1-2 ft thick. It commonly contains quartz sand, phosphate clasts and bored hardgrounds. The Mifflin Member is a wavy-bedded, nodular, fossiliferous, heavily bioturbated limestone. Ranging from 11-13 ft thick, it is the thickest member within the Platteville. Very thin, siliciclastic-rich carbonate beds are intercalated with the nodular, bioturbated limestone giving it an alternating dark gray and light gray pattern. The Mifflin is overlain by a dolomitic, shaly carbonate known as the Hidden Falls Member. It is massive and nonfossiliferous except for subordinate thin, fossiliferous lenses. The Hidden Falls Member ranges from 4-6 ft thick and is recessive in outcrop. The Magnolia Member overlies the Hidden Falls. It is 7-10 ft thick and characterized by fossiliferous shell beds a few inches thick and spaced about every foot in an otherwise nonfossiliferous dolomitic mudstone. The lowermost Magnolia, immediately above the contact with the Hidden Falls, is composed of several interbeds of shaly carbonate, and fossiliferous carbonate. Interbedded shale and fossiliferous carbonate of the Carimona Member (Decorah Shale) lies atop the Magnolia Member (Platteville Formation).

Porosity and Hydraulic Conductivity

Relatively large (visible without magnification) openings called secondary pores are characteristic of the Platteville Formation throughout its extent. There are two general kinds of secondary pores in the Platteville Formation: vertical to subvertical fractures, and bedding parallel (horizontal) partings (BPPs). The openings in these pores, called apertures, generally range from “hairline” fractures with apertures measured in microns, to as wide as several inches. Fractures with even larger apertures, possibly enlarged through dissolution, have been inferred on the basis of hydraulic or geophysical data (e.g. Kelton Barr Consulting 2000). The BPPs are horizontal secondary pore space that preferentially aligns along bedding. Outcrop and large diameter borehole observations indicate that bedding-parallel partings are part of an anastomosing network of elongate apertures developed along discrete stratigraphic intervals (Runkel et al. 2003, 2006b, 2014, 2015).

At the smallest scale the hydrologic properties of the Platteville Formation are similar to most carbonate bedrock in southeastern Minnesota inasmuch as it is a relatively dense, well-cemented unit with minimal matrix porosity and permeability. Therefore, where secondary porosity is negligible, hydraulic conductivity is very low. The lowest measured conductivities are derived from laboratory permeability tests of small diameter (~1 inch) plugs of the formation, at 10^{-7} ft/day or less (Runkel et al. 2003). These same plugs range from about 2 to 3% porosity.

A schematic summary of larger scale tests of hydraulic conductivity (Runkel et al. 2015) is shown in Figure 4. Some tests of discrete intervals, mostly packer tests of 5 ft (or less) lengths of individual boreholes, commonly yield values of less than 10^{-4} ft/day. These are presumably a measure of the hydraulic conductivity of carbonate matrix blocks in which secondary pores are absent or relatively poorly connected and have narrow apertures. Such intervals are most common within the Mifflin Member. Hydraulic conductivity of the Platteville Formation where secondary pores are better developed is orders of magnitude higher. Discrete intervals of a few feet or less have conductivities ranging from a few ft/day to tens of thousands of ft/day (Fig. 4). These intervals are most commonly in the upper part of the Formation, from approximately the middle of the Hidden Falls upward through the Magnolia Member. The highest values (tens of thousands of ft/day) are derived from injection flowmeter logging tests, and represent the hydraulic conductivity of individual BPPs. Flow speeds as fast as 1.25 mi/day measured with dye traces near Camp Coldwater Spring (CCS) (Alexander et al. 2001; Anderson et al. 2011) likely represent flow along such BPPs.

General Hydrogeologic Conceptual Model and Purpose of this Project.

Traditional hydrogeologic classification combines the Platteville Formation with the overlying Decorah Shale and underlying Glenwood shale as the middle part of the Decorah-Platteville-Glenwood Aquitard (Kanivetsky 1978). Across most of its extent within the TCMA it is fully saturated. Hydraulic connection to the water table aquifer is variable. Where covered only with sand and gravel, it is well connected to the water table aquifer. In other areas, where it is covered by Decorah Shale or clay-rich Quaternary sediment, it is confined.

Conditions change near eroded edges of the Platteville Formation. Within several hundred feet of eroded edges along the Mississippi River, where a number of the upper bedrock aquifers discharge, the water in the saturated Platteville is perched on top of the underlying Glenwood shale (Fig. 5). Closer yet to bluff edges (within a few tens of meters) the Platteville itself becomes partly unsaturated. Discharge at the eroded edges occurs as perched springs and seeps. Leakage through the Glenwood shale into the underlying unsaturated St. Peter Sandstone also likely occurs, with subsequent discharge beneath the land surface into the Mississippi River.

Horizontal flow in the Platteville Formation is believed to be dominated by BPPs that are concentrated along discrete stratigraphic intervals (Anderson et al. 2011; Runkel et al. 2015). Stratigraphic correlation of BPPs accommodating flow in boreholes and springs (e.g. Anderson et al. 2011) shows that hydraulically active BPPs are especially clustered in the lowermost approximately 1.5 to 2 ft of the Magnolia Member (Figs. 3, 5), an interval we refer to as the “BPP zone”. BPPs are also common at a position approximating the top of the Mifflin Member, and have been recognized at other positions in the subsurface within the Hidden Falls Member and higher in the Magnolia Member.

The greatly variable and commonly very high horizontal hydraulic conductivity, fast flow speeds, and presence of networks of hydraulically significant BPPs in the Platteville Formation are typical characteristics of fractured rock aquifers, but inconsistent with its traditional classification as an aquitard. However, Anderson et al. (2011) and Runkel et al. (2015) used reconnaissance-level fracture tracing and hydraulic head data to tentatively infer the presence of thin aquitards within the Platteville, at the top and bottom of the Hidden Falls Member (Fig. 5). They suggested that the Platteville has properties of an aquifer in a horizontal direction, but of an aquitard in a vertical direction. The focus of this project was to better constrain if and where discrete intervals within the Platteville can indeed serve as low permeability aquitards that inhibit vertical flow.

STUDY APPROACH AND METHODS

There were two primary activities during this project. One activity was collection of a variety of geologic and hydrologic information from monitor wells. This was accomplished at two sites near the Mississippi River in Minneapolis; one on the University of Minnesota campus and another near Minnehaha Falls (Fig. 2). They are referred to as the “Campus” and “Minnehaha Falls” sites. We used recently developed techniques that include borehole geophysical testing and instrumentation with multiple pressure and temperature sensors. Two monitor wells at each site were instrumented with sensors. A second activity was detailed mapping of vertical fractures at an exposure of the Platteville Formation at the Campus site.

The ultimate goal of providing greater insight into flow through the Platteville Formation is achieved by interpreting the monitor well data within the context of the fracture characteristics mapped at the exposure. Particularly important data from the monitor wells are pressure measurements taken at discrete intervals, which are used to construct profiles of hydraulic head elevation and gradient. Relatively large deflections in hydraulic head across thin stratigraphic intervals in the profiles can be used to identify key low permeability barriers to vertical flow (Meyer et al. 2008, 2013, 2014, 2016). Variability in vertical connectivity across the monitored interval can also be recognized by comparing hydrographs from the monitored zones (e.g. Runkel et al. 2018). Groundwater chemistry was analyzed for some monitor wells, because the distribution of chemical constituents can also provide insight into vertical connectivity.

The fracture mapping is stratigraphically linked to the monitor well information using natural gamma logs. The mapping focused on identifying rock layers or layer contacts where vertical fractures preferentially terminate. Because fractures are the primary pathway for vertical flow, these termination positions could correspond to intervals with low vertical hydraulic conductivity in saturated, subsurface conditions. The terminations, therefore, may correspond to characteristics of the monitor well, such as deflections in hydraulic head elevation. Deflections in vertical hydraulic head profiles recognized elsewhere in the Cambrian-Ordovician aquifer system have previously been suggested to correspond to poor vertical connectivity of fracture sets (Eaton et al. 2007; Meyer et al. 2008, 2014, 2016). However, poor connectivity of vertical fractures could not be independently demonstrated at these study sites because of the sampling bias inherent in the use of vertical boreholes (Terzaghi 1965).

Fracture mapping

To overcome this vertical borehole sampling bias, we mapped the distribution of vertical fractures in a Platteville Formation exposure beneath the Washington Avenue bridge on the east bank of the Mississippi River (Fig. 2). We used procedures similar to those of Underwood et al. (2003), Cooke et al. (2006), Anderson et al. (2011) and Runkel et al. (2018). Photographs and video of the exposure were collected using a drone. Paper copies of the highest resolution photographs were taken into the field where individual fractures were examined for their continuity, marking the traces of each fracture and the termination points with hand-drawn linework on the paper copies. Orientation of individual fractures was measured where exposure permitted. A panoramic collage of photos covering the entire studied exposure was imported into GIS software, where field traces of individual fractures were digitized and attributed with fracture orientations.

Orientation and spacing measurements were used to construct plan-view maps of fractures for individual members of the Platteville Formation. These plan view maps, along with measurements of member thicknesses, were combined to create a 3-dimensional model of fracture networks.

A gamma log of the exposure from the Glenwood shale up through the lower Magnolia Member of the Platteville Formation was acquired using a handheld gamma-ray scintillometer. Measurements were taken at 10 cm increments. Correlation of this gamma log to borehole gamma logs provided the stratigraphic link between the fracture information gleaned from the exposure to that of the monitor wells.

A vertical profile of relative rock strength was also collected. It is based on mechanical rebound values, also collected at 10 cm increments, using a Schmidt hammer placed directly on the rock. This provides insight into variations in rock strength that may correspond to mechanical stratigraphic layers and their contacts, which can dictate where fractures preferentially terminate.

Monitor well testing

A suite of borehole geophysical logs, video logs, and, for some monitor wells, packer tests provided information that guided the design of pressure and temperature sensor installations. These logs were also used as context for interpreting the pressure and temperature data subsequently collected from the sensors. Borehole geophysical logs included natural gamma, caliper, fluid resistivity, and temperature. An acoustic televiewer log was collected in one monitor well. Flow in the monitor wells was measured using an electromagnetic flowmeter in ambient and stressed conditions. Stressed conditions refer to injection of water into monitor wells at rates between 10 and 20 gallons per minute. Some of the logs were collected by a University of Guelph technician, others were collected by the Minnesota Geological Survey. One monitor well was logged by the Minnesota Department of Health using a Hydrolab HL4 multiparameter system with depth, pH, conductivity, dissolved oxygen (LDO), and oxidation-reduction potential sensors.

Pressure and temperature measurements were acquired at discrete intervals using a technique developed and described by Pehme et al. (2014). It is a temporary system which can be deployed to monitor and hydraulically characterize conditions in a borehole in a very detailed manner. The simple system is limited in the number of monitored intervals only by the number of sensors available and space in the monitor well. The system is removable and can be reconfigured as needed and re-used at other locations. The sensor deployment consists of a series of pressure and temperature sensors placed behind a removable poly-urethane (FLUTe®) liner (Fig. 6). The primary sensors used for this project were RBR Duets. These sensors measure pressure (accuracy ~ ±0.05% full scale) and temperature (accuracy ±0.002 ^{0}C). For some deployments, Van Essen Divers were also used to measure both pressure (accuracy ±0.05% f.s.) and temperature (accuracy ±0.1 C). The deployment depths are based on the borehole geophysical logs and other hydrologic information collected from the monitor well. The liner creates a seal that hydraulically isolates successive sampling intervals. In each sampling interval the sensor is surrounded by a plastic weaved covering. The covering ensures the liner is separated from the borehole wall providing hydraulic connection between the formation water and the sensor. The individual sensors are attached to a single deployment line (1/16" low stretch coated wire rope) with a weight (large link chain) attached to the bottom.

Each sensor collected pressure and temperature measurements every ten seconds. The measurements are acquired by removing liners and sensors, and downloading data in the office. Sensors were then restarted for subsequent installations, in some instances with position of the sensor adjusted based on interpretation of previously acquired data. The number of installations and monitoring periods for the wells varied. Multiple installations were performed at three of the four monitor wells. The duration of data collection for individual installations varied from several days to several months.

Water samples for chemical analysis were collected at discrete intervals from two of the monitored wells. One well was sampled using a double packer system with a sample interval between packers of 1.0 ft. Another was sampled by the Minnesota Department of Health using a Solinst Discrete Interval Sampler (Model 425) pressurized by an air compressor. Standard cations and anions were analyzed by a lab in the University of Minnesota Department of Earth Sciences.

FRACTURE MAPPING

Overview of vertical fractures

The vertical fractures in the Platteville Formation are characteristic of all Paleozoic bedrock in this region. They occur in two sets with preferred northwest-northeast orientations that intersect one another to create an approximately orthogonal network in plan view. Individual fractures range in height from less than an inch, where they are commonly closely spaced and constrained to individual beds; to tens of feet, where they are widely spaced and cross many beds. Previous reconnaissance level fracture mapping of the Platteville Formation showed that each member has a distinct style of vertical fractures (Anderson et al. 2011), shown schematically in Figure 5. The Magnolia Member has a high density of vertical to sub-vertical fractures with a wide range in height that give it a blocky appearance in exposures. The Hidden Falls Member has a very high density of vertical to subvertical, mostly curvilinear (conchoidal) fractures. The Mifflin Member has comparatively widely spaced, vertical fractures of great height, typically extending across the entire thickness of the member. The Pecatonica has a closer spacing of vertical, straight fractures with traces that span the thin member. These observations led Anderson et al. (2011) to suggest that across most of its extent, members of the Platteville act as mechanical units and vertical fractures typically terminate at the contacts between the members, which act as mechanical interfaces. Our chief objective in this project was to provide higher resolution vertical fracture termination information than previous efforts. The primary improvements were improved imaging of the exposure, and more intensive tracing of fractures in the field.

Results

A panoramic image of the outcrop, along with an overlay of traced fractures and their termination points is shown in Figure 7. We identified seven thin intervals of strata where vertical fractures preferentially terminate (Fig 8a). These are referred to as preferential termination horizons (PTHs). Among these, a thin (1.5-2.0 ft) interval in the lowermost Magnolia Member has the most pronounced terminations. This interval contains thin beds of intercalated limestone and shaley limestone, and corresponds to the BPP zone, where hydraulically active BPPs are common in boreholes and outcrops. Only eight of 166 (4.8%) traced fractures that intersect the top or bottom of this interval continue past the middle of the interval. Only two (1.2%) entirely cross the interval. Vertical fractures intersecting it from above commonly extend several meters across multiple beds though the Magnolia Member.

Closely spaced fractures of very small heights (a few inches or less) are evident locally within the PTH in the lowermost Magnolia Member, but in most parts of the exposure are difficult to trace due to heavy weathering. These fractures are vertically discontinuous, rarely extending across the entire PTH. Instead they terminate within it, at thin shale-rich beds (Fig. 9). Because of the presence of these smaller-scale fractures, at an even finer evaluation one or more very thin PTHs could conceivably be delineated within the thicker interval we have defined. For example, in several places on the exposure an interval of only a few inches approximating the middle of the more broadly defined lowermost Magnolia PTH appears to show preferential terminations. This thin interval is marked by a darker dashed line on Figure 8a.

Separate consideration of the fractures of greatest heights is important because many of them extend across one or more of the seven PTHs in the Platteville Formation. Such fractures therefore may be direct vertical pathways for flow across those PTHs in saturated subsurface conditions. These fractures are approximately represented at this exposure by those with heights exceeding 2.5 ft and are highlighted in Figure 8b. None of these fractures cross the entire exposed Platteville Formation, consistent with results at other exposures (Anderson et al., 2011). In addition, most of these fractures are contained within the individual members of the formation. All but two of the several fractures that cross most of the exposed Magnolia terminate at the top of the lowermost Magnolia PTH. Those two fractures terminate at or near the bottom of this PTH. Similarly, no individual fracture entirely crosses the Hidden Falls Member. Mifflin Member fractures that can be traced upward into the Hidden Falls terminate in the middle to upper part of that member. Other fractures within the Hidden Falls are contained entirely within the member.

A rock strength profile of the exposure reveals a fairly consistent correspondence to fracture terminations, whereby the intervals with lowest rock strength correspond to positions of PTHs (Fig. 10). This relationship has been well documented in previous studies. Vertical propagation of a fracture in stratified rock commonly continues through material with consistent mechanical properties and ceases where properties such as rock strength abruptly change (e.g. Cooke et al., 2006).

Fracture connectivity, aperture width, and heights are better developed in bedrock that is at or near the land surface compared to the deeper subsurface due to increased weathering and stress release in near-surface conditions (Ferguson, 1967; Nichols, 1980; Wyrick and Borchers, 1981; Gross and Engelder, 1991; Molnar, 2004). Therefore, we produced a hypothetical depiction of fracture characteristics as they might occur where the Platteville Formation is buried in the deeper subsurface and farther from bluff edges (Fig. 11). Our depiction includes narrower apertures, and more limited fracture heights, with even more pronounced terminations at the seven PTHs. Independent evidence that generally supports this depiction includes observations from an underground excavation where apertures of fractures at the bottom of the Platteville Formation progressively narrow with increasing distance from bluff edges (Anderson et al. 2011). In addition, many of the fractures traced across PTHs as part of this study show subtle changes where they intersect these horizons, including diminished aperture, shallower dips, and a more rugose fracture trace. Such changes are typical of fractures that have undergone additional propagation during weathering and stress release when bedrock is at or near the land surface.

Figures 12a and 13 illustrate schematically how spacing and orientations of vertical fractures differ between the members of the Platteville Formation. The similarity of our plan-view depiction of fractures in the Mifflin Member to a map of fractures on the bottom of the Platteville Formation in a nearby underground excavation (Fig. 12b) provides some positive ground-truthing to our mapping methods. The three-dimensional physical model of vertical fractures (Fig 13) will be useful for educational purposes, because it is difficult for many people to visualize geometries in three dimensions. It also provides a physical framework that, in combination with hydraulic conductivity and hydraulic head information, can be used for groundwater modeling.

MONITOR WELL MEASUREMENTS

This section of the report describes the information collected from each of the monitor wells at the Campus and Minnehaha Falls sites. Interpretation of the data, collectively, is provided in subsequent sections. The general geologic and hydrologic conditions at the two sites are shown in map (Fig. 2) and cross section (Fig. 14) views. Conditions at both sites are representative of large parts of the TCMA, whereby groundwater in the Platteville and other bedrock layers flows toward and discharges into the Mississippi River. The Platteville Formation is uppermost bedrock across all of the Minnehaha Falls site.

Isolated remnants of the Decorah Shale locally overlie the Platteville at the Campus site. At both sites, the Quaternary unconsolidated sediment overlying bedrock is dominated by sandy material.

Campus

Williamson Hall

The two monitor wells at the Campus site are referred to as "Williamson Hall" and "Coffman Union" because of their proximity to those buildings. The Williamson Hall well is located about 360 meters northeast of a naturally eroded edge of the Platteville Formation along the Mississippi River (Fig. 14a). A shallower monitor well a few feet from the Williamson Hall well is open to the water table in unconsolidated Quaternary sediment. This well is referred to as the Williamson Hall sentinel well.

Results of borehole geophysical and video logging for the Williamson Hall well are shown in Figure 15. Particularly noteworthy is the ambient flow conditions. Downflow of over 5 gallons per minute originates from BPPs at three or more intervals of the Magnolia Member. The downflowing water exits at BPPs in the lowermost part of the member and within the approximate middle of the Hidden Falls Member. An injection test during flowmeter logging, at a rate of 10 gallons per minute, resulted in all measurable injected water exiting at the BPP in the lowermost Magnolia Member. Hydraulic conductivity for this BPP is calculated at about 2500 ft/day.

Chemistry of water sampled from five discrete intervals reveals some subtle differences within the Platteville (Fig. 16). The uppermost sample, from the upper part of the Magnolia Member, differs from all lower samples in elevated concentrations of chloride, bromide, sodium, phosphorus, and magnesium. This is consistent with the fluid resistivity log (Fig. 15), which measured relatively low resistivity (more mineralized) water across the upper Magnolia Member. The uppermost water sample also has lower concentrations of iron and potassium compared to lower samples. The four samples from lower in the Williamson Hall well show some variability amongst them, but no discernable, consistent pattern with depth.

Seven installations of pressure and temperature sensors were conducted in the Williamson Hall well over a period of nearly three years. A sensor was also placed below static water in the sentinel well to collect information from the water table aquifer. Some sensor positions in the Williamson Hall well were adjusted between installations in a manner whereby we acquired measurements across nearly the entire extent of the Magnolia and Hidden Falls members. Hydraulic head elevation and gradient profiles from all installations (Fig 17) are consistent in showing an overall downward decrease in hydraulic head, i.e. a downward gradient, from the water table aquifer to the lower part of the Mifflin Member. The hydraulic gradient profiles reveal differences in gradient magnitude between parts of the Platteville Formation. The

Magnolia and upper Hidden Falls Member are characterized by moderate to large gradients that are variable in direction (upward or downward) during different monitoring periods. The lower Hidden Falls and all of the Mifflin Member are associated with very small gradients (variable in direction) over time.

The most pronounced, consistent deflection in hydraulic head elevation in the Williamson Hall well is present within a 1 ft interval corresponding to the upper part of the BPP zone in the lowermost Magnolia Formation (Fig. 17). Hydraulic head decreases as much as 11 feet across a vertical distance of less than one foot. This is best displayed by the profiles from pressure measurements collected in the final four installations, when sensors were most closely spaced across the lower Magnolia and uppermost Hidden Falls members.

Representative hydrographs from one of the monitoring periods for the Williamson Hall well are shown in Figure 18a. Comparison of the hydrographs to one another (Fig. 18b) highlights differences in how hydraulic head changed from June to October at various monitor intervals across the Platteville Formation. The comparison reveals an apparent two-fold division across the formation. Hydrographs for the lowermost part of the Magnolia Member down to the lowermost Mifflin Member are nearly identical to one another over this time period. Hydrographs higher in the Platteville, across the remaining part of the Magnolia Member, are generally similar to one another, with minor variability. As a group they are distinctly different from the hydrographs lower in the formation.

Temperature profiles from the same monitoring period (Fig. 18c) show a decrease in temperature with depth. The highest monitor interval in the Platteville Formation differs from all monitor intervals below it in having distinctly warmer temperatures, and also showing small-scale variability over short spans of time (a more rugose temperature profile). Another notable feature in the profiles is that temperatures in the middle Magnolia to upper Hidden Falls are clustered, and distinctly warmer than those in the middle Hidden Falls to the bottom of the Mifflin Member. The Mifflin Member profiles show a more consistent trend of decreasing temperature with depth.

Coffman Union

The Coffman Union well is located about 75 meters from the naturally eroded edge of the Platteville Formation, and within 30 meters of an excavated edge in a nearby underground parking garage (Fig. 14b). The Platteville is largely dewatered in the garage, with the exception of small seeps. There are three similarly constructed monitor wells open to the Platteville Formation within 90 meters of the Coffman Union well, with the closest at about 35 meters.

Results of borehole geophysics and video logging for the Coffman Union well are shown in Figure 19. There is no measurable ambient flow in this monitor well (i.e. if present, flow is less than 0.1 l/min). Suspended sediment and neutrally buoyant masses of microbes visible in video logs similarly show no indications of flow. An injection test during flowmeter logging, at a rate of 8 gallons per minute, resulted in all measurable injected water exiting at a BPP in the lowermost Magnolia Member. Hydraulic conductivity for this BPP is calculated at about 8400 ft/day. Flow logging of the three nearby monitor wells at Coffman Union yielded similar results in showing no measurable ambient flow. Injection logging in one of the wells also indicated the presence of a BPP with high hydraulic conductivity in the lowermost Magnolia Member.

Three installations of pressure and temperature sensors were conducted in the Coffman Union well over a period of about 10 months. At the end of both the first and second installation periods, there was mild resistance when the string of sensors was pulled, and upon extraction there was sediment clinging to the link chain and lowermost sensor. This led to the concern that the lowermost sensor was embedded in fine sediment and microbial material that had collected in the lower part of the borehole. A tag of hole depth, in comparison to depths indicated by the drilling record and geophysical logs collected years earlier, indicated the lower part of the borehole had filled with at least a few feet of material. Prior to the third installation, we scraped the sides of the open hole with a rubber skirt encircling a heavy metal cylinder to remove scale, sediment and microbes from the borehole wall. We then removed about four feet of material filling the lower part of the hole using portable coring and bailing equipment. This allowed placement of lowermost probes in a position well above any sediment for the third installation.

Hydraulic head and gradient profiles from all installations (Fig. 20) are consistent in showing an overall downward decrease in hydraulic head, i.e. a downward gradient. The hydraulic head profiles from all three monitoring periods contrast to the Williamson well in having relatively small gradients. The largest of these gradients, measured during the first monitoring period across the lower part of the Hidden Falls Member, may be unreliable because of the sensor placement in material filling the bottom of the hole. The pressure measurements from the lowermost sensor in the second monitoring period may also be impacted to some extent by the same phenomenon.

A distinctive feature of hydrographs from the Coffman Union well (Fig. 21a) is the abrupt, short term (seconds to minutes), upward and downward spikes in hydraulic head of as much as two feet. The spikes were recorded at all monitor intervals with the exception of the interval that includes the hydraulically significant BPP in the lowermost Magnolia Member. Comparison of the hydrographs to one another (Fig 21b) shows extreme similarity over time between all monitored intervals, aside from variability in magnitude and timing of the spikes described above.

Temperature profiles (Fig. 21c) show a generally consistent increase in temperature with depth. An exception is slight cooling downward between the lowermost two monitored intervals. The most distinct feature is the abrupt changes in temperature. Many of these changes correspond in time to the spikes in hydraulic head elevation.

Minnehaha Falls

B-12

The two monitor wells near Minnehaha Falls are referred to as “B12” and “B13” (Figs. 2, 14c). Monitor well B12 is near Minnehaha Creek about 430 meters northwest of the eroded edge of the Platteville Formation. It is 101 meters southeast of a cluster of five Platteville monitor wells on the opposite (west) side of Minnehaha Creek. Another monitor well about 30 meters north of B12 is open to the upper part of the St. Peter Sandstone. Results of borehole geophysics and video logging for B12 (Fig. 22) show ambient flow conditions highlighted by strong downflow and some upflow in different parts of the open hole. Downward flowing water enters the hole through one or more BPPs in the upper Magnolia Member and upward flowing water at a BPP in the upper one foot of the Mifflin Member. These flows converge and exit the borehole at a BPP in the lowermost Magnolia Member. Minor upward flow may also be present lower in the borehole across the Mifflin Member. Ambient flow logging of three of the monitor wells clustered on the west side of Minnehaha Creek, conducted in July, 2016, also revealed upflowing water entering the boreholes within the upper 1.5 feet of the Mifflin Member, exiting at BPPs within the middle Hidden Falls to lowermost Magnolia Member. Those results are illustrated and discussed in the interpretation section of this report.

Geophysical logs collected by the Minnesota Department of Health show that downflowing water across the Magnolia Member is higher in fluid conductivity and lower in temperature than the upflowing water originating deeper in the open hole (Fig. 22). An injection test during flowmeter logging, at a rate of 20 gallons per minute, resulted in all measurable injected water exiting at the BPP in the lowermost Magnolia Member. Hydraulic conductivity for this BPP is calculated at about 2100 ft/day.

The chemistry of water collected at discrete intervals of monitor well B12 (Fig. 23) shows variability in a manner consistent with flow, conductivity, and temperature logs. There are distinct chemical differences between downflowing and upflowing water. Downflowing water originating from the upper Magnolia Member is higher in chloride, phosphorus, and manganese than the upflowing water originating lower in the open hole. In addition, water in the lower Mifflin Member may differ from uppermost Mifflin water, based on concentrations of some constituents, such as having relatively high sulfate and low chloride concentrations.

Two installations of pressure and temperature sensors were conducted in monitor well B12 over a period of about one month between May and June. The St. Peter sentinel well was also monitored for pressure and temperature. The direction (upward or downward) of vertical gradients in monitor well B12 are generally consistent with flow-logging results, showing a downward gradient across the Magnolia Member, and an upward gradient across the upper Mifflin and Hidden Falls members (Fig. 24). Gradient directions lower in the Platteville are inconsistent between the first and second monitoring intervals, which could reflect transient change in head, or development (enhanced permeability) of the hole during liner insertion and removal.

The largest consistent head deflection over both monitoring periods is across an approximately 1.5 ft interval in the lower Magnolia Member, including the uppermost part of the BPP zone. The hydraulically significant BPP slightly lower in the Magnolia has the lowest hydraulic head elevation in the borehole. The second monitoring period also shows relatively moderate gradients across the lower Hidden Falls and uppermost Mifflin Members.

Comparing variability in hydrographs from the B12 monitoring well is more difficult than for the hydrographs from wells at the campus site because the duration of monitoring was brief. Hydrographs from the first monitoring period for well B12 show no obvious differences between the monitored intervals. Hydrographs from the second installation (Figs. 25a,b) show mostly subtle variability among the intervals. Nine of the intervals, from the uppermost Magnolia to the lower Mifflin Members, are generally similar to one another. Within that grouping, the two highest intervals, across the upper to middle Magnolia Member, are nearly identical to one another, as are pairs of intervals in the upper and lower parts of the Mifflin Member. Hydrographs from two intervals, in the lower Magnolia and along the Pecatonica-Glenwood contact, are distinct from all other monitored intervals.

Temperature profiles for the second installation show two distinct clusters among the monitored intervals (Fig. 25c), in a manner consistent with borehole temperature logs. Monitored intervals across the Hidden Falls down to the upper Glenwood shale have relatively warm temperatures, and smooth profiles showing little short-term variability. In contrast, intervals across the Magnolia Member are clustered at about one degree C colder temperatures, and have a more irregular profile reflecting small magnitude, short term variability. This variability decreases with depth across the Magnolia Member.

B-13

Monitor well B13 is about 190 meters from well B12, and about 250 meters west of the eroded edge of the Platteville Formation (Fig. 14c). Results of borehole geophysics and video logging are shown in Figure 26. Ambient flow conditions are dominated by downflowing water that enters the hole through BPPs and possibly vertical fractures that are clustered within about one foot of casing bottom, in the upper Magnolia Member. Downflow is about 4 gallons/minute, and exits mostly at a BPP in the lowermost Magnolia Member. An injection test during flowmeter logging, at a rate of 18 gallons per minute, resulted in all measurable injected water exiting just below casing, the same interval that sourced most of the ambient downflow. Hydraulic conductivity for this interval is calculated at about 11,000 ft/day.

One installation of pressure and temperature sensors was conducted in monitor well B13 over a period of 10 days in June. Gradients across the monitored intervals (Fig. 27) are all downward, with the steepest gradient across the lower Magnolia Member. The next largest gradients are across the lower Hidden Falls and uppermost Mifflin members.

Hydrographs in the upper part of the Platteville Formation are variable (Fig. 28). The monitored intervals in the middle and top of the Hidden Falls are similar to one another, but differ from those in the Magnolia Member. Hydrographs for monitor intervals lower in the Platteville (uppermost Mifflin down to the Pecatonica-Glenwood contact) are generally similar to one another, including the presence of a very abrupt drop in hydraulic head elevation on June 8.

Temperature profiles show a consistent increase in temperature with depth. The temperature gradient is steepest across the lower part of the Magnolia Member.

INTERPRETATION

Our interpretation focuses on addressing the primary purpose of the project: identifying stratigraphic intervals that have low vertical hydraulic conductivity (Kv) and therefore may hinder vertical transport of contaminants. Interpretations are made largely on the basis of hydraulic gradient and head elevation profiles from all four principle monitor wells, considered in the context of PTHs identified from fracture mapping (Fig. 29), and additional hydrologic information such as packer tests and flow logging (Figs. 30 and 31). The most marked overall contrast in hydraulic head profiles among the four wells is the absence of any large magnitude gradients in the Coffman Union monitor well (Fig. 29). Even the largest gradients in the Coffman Union well are comparable in magnitude to the smallest gradients in the other three monitor wells. The Coffman Union profiles are particularly distinct from the nearby Williamson Hall profiles in the absence of a hydraulic head elevation deflection across the lowermost Magnolia Member, and in the similarity of the hydrographs collected from individual monitored intervals.

The absence of large gradients in the Coffman Union well, particularly across the lower Magnolia and Hidden Falls members, is interpreted to reflect physical breaching of PTHs close to this well. This includes the nearby (< 30 m) excavated edge of the entire Platteville Formation in an underground parking garage (Fig. 14b), and the three monitor wells with open holes from the Magnolia member down to Mifflin Member. Collectively, these natural and anthropogenic breaches of PTHs would lead to relatively good vertical connectivity across the lower Magnolia and Hidden Falls members in this area. The interpretation of enhanced connectivity across the Platteville Formation near an eroded edge is independently supported by observations in an underground excavation on the west bank of the University of Minnesota. Fracture apertures and vertical leakage through the formation in that excavation are significantly increased within about 80 meters of the eroded edge of the formation (Anderson et al. 2011). The pronounced and very abrupt changes in hydraulic head elevation and temperature in the

Coffman Union well may also reflect anthropogenic impact, perhaps in some manner related to conditions in the nearby underground parking garage. However, we have not yet carefully evaluated those data.

In comparison to conditions at the Coffman Union well, the other three monitored wells show indications of one or more low Kv intervals in the Platteville Formation. A thin low Kv interval is most evident in the Williamson Hall dataset (Fig. 30). It is about one foot thick, in the lower part of the Magnolia Member between 59-60 feet depth. It corresponds to the approximate upper one-half of the lower Magnolia PTH identified from nearby fracture mapping. In the monitor well, this upper part of the PTH corresponds to the largest head deflection, and in addition separates two distinct groupings of hydrographs (Fig 18). A large hydraulic head deflection separating two distinct groups of hydrographs was also documented in the St. Lawrence Aquitard by Runkel et al. (2018), and similarly interpreted to represent a low Kv interval. Additional measures of hydraulic conditions support the presence of a low Kv interval at this position in the Williamson Hall well. Measurements of hydraulic head elevation using a single packer indicate poor vertical connectivity in the rock surrounding the borehole between a depth of 59 to 60 ft. In addition, ambient flow conditions require the presence of a low Kv interval that includes (although is not exclusive to) this same interval of strata.

We interpret vertical connectivity across the middle to upper Magnolia at Williamson Hall to be greater than across the low Kv interval in the lowermost part of the member. Although hydraulic gradients are variable over time in both direction and magnitude, they are consistently smaller than the large gradient across the lowermost Magnolia (Fig. 29). Furthermore, the hydraulic head elevations from packer tests are indicative of relatively good vertical connectivity at depths shallower than 59 ft (Fig. 30). This suggests that the PTHs in the middle to upper Magnolia identified from fracture mapping are not of sufficiently low Kv to cause recognizable discrete deflections in hydraulic head. The common presence of fractures vertically spanning much of the Magnolia Member (Fig. 8b) likely accounts for the relatively good vertical hydraulic connectivity across those PTHs.

Lower in the Platteville Formation, gradients are relatively small in the Williamson Hall well, with the largest corresponding to the lowermost one foot of the Magnolia and upper two feet of the Hidden Falls members (Fig. 29). This is suggestive of relatively poor vertical connectivity, which is supported by hydraulic head measurements from packer tests (Fig. 30). Gradients across the middle Hidden Falls down to the lowermost Mifflin Member are all smaller than gradients higher in the Platteville, which, by itself, could be considered an indication of relatively good vertical connectivity across that entire part of the Platteville Formation. Such an interpretation, however, is not entirely consistent with the results of fracture mapping, which include PTHs in the middle Hidden Falls member and across the Hidden Falls-Mifflin contact. Information from the Minnehaha Falls site provides additional insight into vertical connectivity across that part of the Platteville Formation.

Monitor wells B12 and B13 at Minnehaha Falls have some characteristics generally similar to the Williamson Hall well, particularly across the Magnolia Member, but also have hydrologically more dynamic and variable conditions lower in the Platteville. This similarity is evidence for poor vertical connectivity across the lowermost Magnolia Member. Although sensor spacing was not sufficient to identify a low Kv interval to the level of stratigraphic resolution at Williamson Hall, the hydraulic head profiles do indicate a deflection in hydraulic head corresponding to the upper part of the lowermost Magnolia PTH (Fig. 29). The position of one or more potential low Kv intervals based on ambient flow logs in B12 and B13 do not precisely delimit such an interval, but are consistent with an interpretation that the upper part of this PTH provides the hydraulic separation necessary to sustain ambient flow (Fig. 31). Higher in the Magnolia Member the hydraulic head elevation profiles are closer to vertical, showing only very small gradients across the middle to upper Magnolia Member. This suggests comparatively good vertical connectivity across that part of the Magnolia member.

The presence of low Kv units within the Hidden Falls to uppermost Mifflin Member of the Platteville at the Minnehaha Falls site are best expressed in monitor well B12. Water temperature and chemistry profiles indicate poor vertical connectivity across all or parts of the Hidden Falls to uppermost Mifflin Member (Figs. 23, 25c). Upflowing water originating from the uppermost Mifflin Member is markedly warmer and more dilute than the downflowing water originating from the Magnolia Member. The largest hydraulic gradients below the Magnolia member, recorded during the second installation period, correspond to the PTHs in the middle Hidden Falls Member and along the Hidden Falls-Mifflin contact. Potential intervals of low Kv in this same part of the section are also recognized on the basis of correlated ambient flow logs of well B12 and three of the Platteville monitor wells on the west side of Minnehaha Creek (Fig. 31). Collectively these data are indicative of low vertical connectivity across the lower half of the Hidden Falls and uppermost Mifflin members. Considered in context with fracture mapping, we interpret the presence of two distinct low Kv intervals that correspond to the PTHs in the middle Hidden Falls and along the Hidden Falls-Mifflin contact.

Relatively good vertical connectivity is interpreted for the Mifflin Member. Hydraulic head profiles across the member in wells B12, B13, and Williamson Hall all show no pronounced deflections and relatively small gradients. Hydrograph comparisons for monitored intervals across the Mifflin in wells B13 and Williamson Hall (Figs. 18, 28) are also indicative of potentially better vertical connectivity than across the low Kv intervals higher in the Platteville Formation. Relatively good conductivity across the entire Mifflin Member, inferred from monitor well hydrologic information, is consistent with the results of fracture mapping in that no PTHs are present within the member.

DISCUSSION

The consistent lithology, material properties, and fracture characteristics of the Platteville Formation across the TCMA suggests that the three low Kv intervals we identified in this project can reasonably be expected to be present in the Platteville across all of the TCMA. Therefore, our hydrogeologic subdivision of the formation into intervals of relatively good and poor vertical connectivity (Fig. 29) can likewise be applied across all of the TCMA. Lateral variability in vertical connectivity across the low Kv intervals should be expected, but in a predictable fashion. Greater connectivity will occur within a few tens of meters of eroded edges of the Platteville, and close to boreholes with open-hole intervals that cross low Kv intervals.

It is important to understand that our subdivision of the Platteville into lower and higher Kv intervals (Fig. 29) expresses *relative* differences in vertical connectivity. It does not imply that each of the three low Kv intervals quantitatively have similarly low Kv. Nor does it imply that the parts of the Platteville Formation between the low Kv intervals are uniformly well connected in a vertical direction. Instead it is likely that they internally vary in vertical connectivity. An example may be expressed in data from the Williamson Hall well across the middle to uppermost Magnolia Member. The uppermost Magnolia is associated with distinctly warmer and more variable temperatures, and a higher chloride concentration, than lower in the member. This indicates groundwater in the uppermost part of the Magnolia may be better connected to the water table aquifer than the middle Magnolia, even though we depict this entire part of the section as relatively well connected.

There may be more low Kv intervals within the Platteville Formation than we were able to recognize with our data. Although abrupt deflections of hydraulic head elevation are sound evidence for the presence of a low Kv interval, the absence of deflections does not necessarily indicate the absence of a low Kv interval. Sufficient stresses within the flow system across a low Kv interval must also be present to produce a deflection in a hydraulic head profile (e.g. Meyer et al. 2014, 2016). As an example, we interpret the absence of large, abrupt deflections across PTHs in the middle Hidden Falls and along the Hidden Falls-Mifflin contact in the Williamson Hall well to reflect a position in the flow system were hydraulic head differences are muted, rather than the absence of an interval of strata with low Kv.

Among the new insights resulting from this project, the most unanticipated was that connectivity between vertical fractures crossing the Magnolia Member and the BPPs common in the lowermost Magnolia appears to be, at least locally, very poor. Earlier conceptual models (Anderson et al. 2011; Runkel et al. 2015), depicted strong connection of these vertical fractures to the lowermost Magnolia BPPs. Therefore, our expectation was that hydraulic head elevation profiles would have relatively insignificant gradients from the uppermost Magnolia Member down to *and including* lowermost Magnolia BPPs that are present in most boreholes. We also expected that Magnolia fractures, especially those of great height, would commonly penetrate fully into the BPP zone in outcrop, providing physical connection to individual BPPs. Instead, borehole hydrologic data as well as fracture mapping are suggestive of poor connectivity. It is possible that BPPs in the lowermost Magnolia are commonly poorly connected to the larger-scale vertical fracture networks higher and lower in the Platteville. This poor connectivity of BPPs to vertical fractures may also apply to hydraulic BPPs that have been identified within or close to the PTHs in the middle of the Hidden Falls and along the Hidden Falls-Mifflin Member contact.

IMPLICATIONS AND USES OF RESULTS

The recognition of at least three low Kv intervals within the Platteville Formation has implications for contamination prevention and remediation strategies. Particularly important is the relevance to how monitor wells are constructed, and how data from them are interpreted. Conventional monitor well construction at contamination sites includes open hole intervals that cross the low Kv intervals in the Platteville Formation. This standard practice could have several deleterious outcomes. One is that intervals of Platteville Formation with distinctly different water chemistry within the open hole of an individual monitor well are likely to go unrecognized. Conditions in monitor well B12, which had at least two distinct hydrochemical facies, are a good example of this potential problem. A conventionally collected water sample from well B12 would likely consist of either a blend of the two chemically distinct waters, or be dominated by only one of them. The latter scenario may be reflected in the water chemistry results from Platteville monitor wells near well B12 on the west side of Minnehaha Creek. Samples from those wells all had markedly lower chloride concentrations than Upper Magnolia water in B12 (Alexander, 2016). This suggests that the samples were dominated by the upward flowing water originating from the Mifflin Member in those wells.

Another problematic outcome of conventional monitor well construction is that the breaching of low Kv intervals across the open hole could allow downward transport of contaminants to lower parts of the Platteville Formation that under natural conditions would have been better protected. Strong ambient downflow in the Williamson Hall, B12 and B13 monitor wells is a good example of how this might occur.

Potentiometric maps used to infer groundwater flow directions may also be of diminished quality if based on measurements collected from conventional monitor wells. Hydraulic head elevations collected from such wells could represent a blend of distinctly different hydraulic heads within the open hole interval. For example, the blended static water level elevation in the Williamson Hall well is as much as 11 feet lower than the hydraulic head elevation of the upper part of the Magnolia Member. The use of blended head elevations may prevent an investigation from discriminating variable groundwater flow directions for different intervals of the Platteville. Differing flow directions at this scale were demonstrated by Barr Engineering at a site where Magnolia head levels were mapped separately from lowermost Decorah Shale (Carimona Member) head levels (Barr Engineering, 1983).

Predicting flow through aquifers and aquitards is often ultimately accomplished using groundwater models. The models can help predict not only the movement of contaminants, but also water budgets. The latter can provide guidance for water management engineering inherent to many of the construction projects in central TCMA, and for groundwater-surface water modelling, such as within the Minnehaha Creek Watershed. The results of our project such as the three dimensional depiction of fractures, and the relative differences in vertical connectivity across the Platteville Formation can be used in such models to improve their accuracy.

The relevance of our results to how groundwater contamination is characterized and remediated, and how flow is modelled, apply not only to the Platteville Formation, but to all fractured rock aquifers and aquitards in Minnesota. We therefore encourage greater application of more rigorous techniques such as discrete multilevel monitoring. The recently developed methods we used in this investigation (Pehme et al. 2014) offer an inexpensive and efficient way to do so.

FIGURE CAPTIONS

Fig. 1. Shallow groundwater conditions in the central part of the Twin Cities Metropolitan area (TCMA). Groundwater is commonly contaminated in the Platteville Formation. This investigation combines information from monitor wells and fractured rock exposures to better predict contaminant transport.

Fig. 2 **A**) Bedrock geologic map of the TCMA, showing location of monitor wells and rock exposure investigated at the Campus and Minnehaha Falls study sites. Selected locations where pronounced groundwater contamination is known in the Platteville Formation are also shown: RTC- Reilly Tar and Chemical, KC- Koppers Coke, GMEH- General Mills/East Hennepin Avenue FMGW- Former Minneapolis Gas Works, MLAC- Minnesota Library Access Center, SP- Superior Plating. Bedrock geology depicted in Hennepin County from Retzler (2018); elsewhere from Mossler (2013. **B**) Zoomed view of two principle sites investigated for this project, showing locations of cross sections A, B and C in Fig. 14

Fig. 3 Generalized stratigraphic column, and outcrop photo showing the lithology, thickness, and nomenclature for the Upper Ordovician formations in the TCMA. The Decorah Shale thickness is variable across the study area and locally absent. The spring count lists the number of springs emanating from a specific stratigraphic interval. Hydraulic BPPs refer to bedding plane partings through which ambient or induced flow occurred during flowmeter logging. Results are from a total of 12 monitor wells.   The natural gamma log (units API-G) shown on the right is collected from a water well (County Well Index Unique Number 763752).

Fig. 4. Summary of typical horizontal hydraulic conductivity values from discrete interval tests of the Platteville Formation. From Runkel et al. (2015).

Fig. 5 Hydrogeologic conditions in the heavily fractured Platteville Formation in cross-sectional view. The cross section is perpendicular to groundwater flow direction, spanning from where Platteville is fully saturated to an eroded edge along the Mississippi River, where it dewaters. The focus of this investigation was to determine where discrete barriers to vertical flow, such as the ones shown schematically here, are present in the Platteville. Modified from Anderson et al. (2011).

Fig. 6. Schematic illustration of installation of multiple pressure and temperature sensors in a lined monitor well. From Pehme et al. (2014).

Fig. 7 Platteville Formation exposure used to map fractures, beneath Washington Avenue Bridge along east bank of Mississippi River. **A)** Collage of photos from drone, stitched together in a panorama. **B)** Black lines represent fractures traced on the exposure. Members of the Platteville Formation shown to the right. Location in Fig. 2.

Fig. 8. **A)** Traced fractures, termination points identified on fractures, and preferential termination horizons (PTHs) in mapped Platteville exposure shown in Fig. 7. **B)** The same information as in A) but showing only fractures with heights greater than 2.5 ft. The darker brown dashed line corresponds to a particularly thin PTH that may be present within the thicker PTH in the lowermost Magnolia Member.

Fig. 9. Lowermost 1.5 ft of Magnolia Member showing fractures with small height within the BPP zone.

Fig. 10. Rock strength compared against PTHs identified by fracture mapping of Platteville exposure. The rock strength is based on rebound measurements using a Schmidt hammer. Uppermost part of the exposure was inaccessible and, therefore, no measurements were taken.

Fig. 11. Schematic depiction of fractures and PTHs in the Platteville Formation. **A)** Depicts fractures as observed in rock exposure, **B)** hypothetical depiction of fractures in deeper subsurface where they can have smaller heights, be more sparsely distributed, and have narrower apertures.

Fig. 12. Plan view depiction of fractures in the Platteville Formation. **A)** Compares the spacing and orientations of fractures within the Magnolia and Mifflin members of the Platteville. Note: (fractures in the Hidden Falls Member are too irregular in plan view to measure adequately to determine an average orientation. **B)** Comparison of mapped Mifflin Member fractures shown in A) to those measured in an underground excavation located 310 meters to the west of the exposure.

Fig. 13 Three-dimensional block model of fractures in the Magnolia, Hidden Falls, and Mifflin members of the Platteville Formation.

Fig. 14. Geologic cross sections displaying conditions at sites where hydrologic information was collected from monitor wells. Campus site is represented in cross sections **A)** and **B)** for the Williamson Hall and Coffman wells, respectively. **C)** Depicts the Minnehaha Falls site including wells B12 and B13. Potentiometric surfaces for the water table (WT), Platteville (OPVL) and St. Peter Sandstone (OSTP) are shown as blue lines. Fig. 2 shows cross section locations.

Fig. 15. Borehole geophysical and video log data for the Williamson Hall well. Ambient downflow originating from BPPs in at least three positions in the Magnolia Member exits the hole at BPPs in the lowermost Magnolia and upper part of the Hidden Falls Members. Injected water (10 gal/minute) exited the hole at the lowermost Magnolia BPP.

Fig. 16. Selected water chemistry from five discrete intervals in the Williamson Hall well. Samples were collected with double packers spaced 1.0 ft apart. Depths in feet of samples represent midpoint between the two packers. Position of samples also shown in Fig. 15.

Fig. 17. Hydraulic head elevation and gradient profiles for the Williamson Hall and nearby sentinel well (labelled). Shows selected head elevations and gradients representative of each of the seven monitoring periods (seven installation events).). An overall downward gradient is highlighted by a pronounced deflection in head elevation across the lowermost Magnolia Member. Dates for selected data are listed in the column headers. Each of the markers along the head elevation profiles are placed at a depth corresponding to the center of the sensor. The spacing between the blue and red blocks depicting hydraulic gradient corresponds to the length of the sensor.

Fig. 18. Hydrographs and temperature plots from the Williamson Hall well from the fifth monitoring period. **A)** Hydrographs plotted as elevation of hydraulic head over time. The large drop in head elevation between sensors two and five corresponds to the large deflection in the hydraulic head profile across the lowermost Magnolia Member in Fig. 18. Depths of sensor tops and their stratigraphic position are shown on the right. The sensor at 12.01 ft was in the sentinel well. All others were in the Williamson Hall well. **B)** Comparison of changes in hydraulic head in monitored intervals. Note that the hydrographs in the lowermost Magnolia through the Mifflin Member are more similar to one another than to the cluster of hydrographs from higher positions

in the Magnolia Member. **C)** Temperature profiles from the same monitoring period. See text for discussion.

Fig. 19. Borehole geophysical and video log data for the Coffman Union well. Noteworthy is the absence of measurable ambient flow. Injected water (8 gal/minute) exited the hole at the lowermost Magnolia BPP.

Fig. 20. Hydraulic head elevation and gradient profiles for the Coffman Union well. Shows selected head elevations and gradients representative of each of the three monitoring periods (three installation events) for this well. Characterized by relatively very small downward gradients. Dates for selected data are listed in the column headers.

Fig. 21. Hydrographs and temperature plots from the Coffman Union well from the third monitoring period. **A)** Hydrographs plotted as elevation of hydraulic head over time, showing the relatively small decreases in head elevation downhole. Depths of sensor tops and their stratigraphic position are shown on the right. **B)** Comparison of changes in hydraulic head in monitored intervals. Note the similarity of the hydrographs to one another. **C)** Temperature profiles from the same monitoring period. The very abrupt increases and decreases in hydraulic head elevation and temperature are discussed in the text.

Fig. 22. Borehole geophysical and video log data for monitor well B12. Dynamic ambient flow conditions are highlighted by strong downflow and upflow in different parts of the open hole that converge and exit the hole at a BPP in the lowermost Magnolia Member. Fluid temperature, conductivity, pH, and ORP (oxidation-reduction potential) logs also have signatures reflecting these flow conditions (see text for discussion). Injected water (20 gal/minute) exited the hole at the lowermost Magnolia BPP.

Fig. 23 Selected water chemistry from four intervals in the monitor well B12. Samples were collected with a Solinst Discrete Interval Sampler (Model 425) pressurized by an air compressor. Position of samples also shown in Fig. 22. Differences in chemistry among the four samples show a distinction in some constituents between upflowing and downflowing water, discussed in the text.

Fig. 24. Hydraulic head elevation and gradient profiles for monitor well B12 and the St. Peter Sentinel well (labelled). Shows selected head elevations and gradients representative of each of the two monitoring periods (two installation events) for these wells. The gradients are generally consistent with flow logging, showing a downward gradient across the Magnolia Member and an upward gradient across the lower Platteville Formation. The hydraulic head elevation profile on the right shows data from the B12 well only at an expanded horizontal scale.

Fig. 25. Hydrographs and temperature plots from monitor well B12 from the second monitoring period **A)** Hydrographs plotted as elevation of hydraulic head over time. Depths of sensor tops and their stratigraphic position are shown on the right. **B)** Comparison of changes in hydraulic head in monitored intervals. **C)** Temperature profiles from the same monitoring period. Noteworthy is the two distinct groupings, with the Magnolia Member water markedly colder than water lower in the Platteville Formation. See text for discussion.

Fig. 26. Borehole geophysical and video log data for monitor well B13. Ambient flow conditions are highlighted by strong downflow entering about 0.5 ft below casing bottom, and exiting the hole at a BPP in the lowermost Magnolia Member. Note that the fluid resistivity log indicates

downflowing water from the Magnolia Member is markedly more resistive (less dilute) than water immediately lower in the hole.

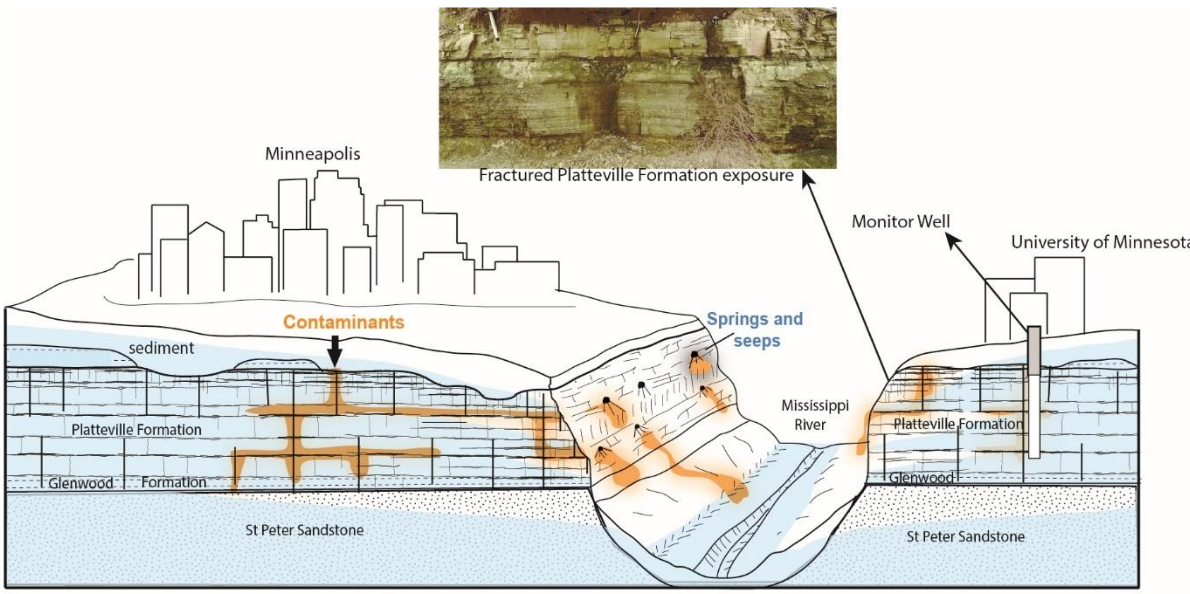
Fig. 27. Hydraulic head elevation and gradient profiles for monitor well B13 that shows selected head elevations and gradients representative of the single monitoring period (one installation event). The gradients are generally consistent with flow logging, showing a strong downward gradient across the lower part of the Magnolia rMember.

Fig. 28. Hydrographs and temperature plots from monitor well B13. **A)** Hydrographs plotted as elevation of hydraulic head over time. Depths of sensor tops and their stratigraphic position are shown on the right. **B)** Comparison of changes in hydraulic head in monitored intervals. **C)** Temperature profiles from the same monitoring period. See text for discussion.

Fig. 29. Compilation of representative hydraulic head elevation and gradient profiles from the four instrumented monitor wells. Context of position of hydraulic BPPs identified via flow-logging, and PTHs identified by fracture mapping of Platteville exposure at Campus site. Also highlighted are the PTHs that correspond to low Kv intervals identified from monitor well data, and the intervals between them inferred to be better hydraulically connected vertically.

Fig. 30 Compilation of data from fracture mapping and measurements in the Williamson Hall monitor well that provide support for the presence of a low Kv interval(s) in the lower part of the Magnolia Member. The packer tests show a similarity in hydraulic head elevations above and below the inflated packer across all of the Magnolia Member down to a depth of 58.75 ft, indicating good vertical connectivity. When inflated packer reaches a depth corresponding to the upper part of the PTH (A), the large difference in hydraulic head elevation above and below the packer indicate an interval with low Kv has been sealed by the packer. This low Kv interval continues down to a depth of 60.53 ft., shown where heads above and below the packer (B) become more similar to one another. Collectively the different measures of connectivity are consistent in discerning a one-foot interval (59-60 ft) in the upper part of the PTH identified via fracture mapping.

Fig. 31 Ambient flowmeter logs from the Platteville Formation monitor wells at the Campus and Minnehaha Falls sites, correlated stratigraphically to one another. Ambient flow requires the presence of one or more low Kv intervals adequate to maintain different hydraulic head elevations for entrances and exits of flowing water. The potential positions of such low Kv intervals for each ambient flow log is shown. They are consistent with the positions of all or parts of identified PTHs and with some deflections in hydraulic head elevation.



Minneapolis
Fractured Platteville Formation exposure
Monitor Well
University of Minnesota
Contaminants
Springs and seeps
sediment
Platteville Formation
Glenwood
Formation
Mississippi River
Platteville Formation
Glenwood
St Peter Sandstone
St Peter Sandstone

Fig. 1

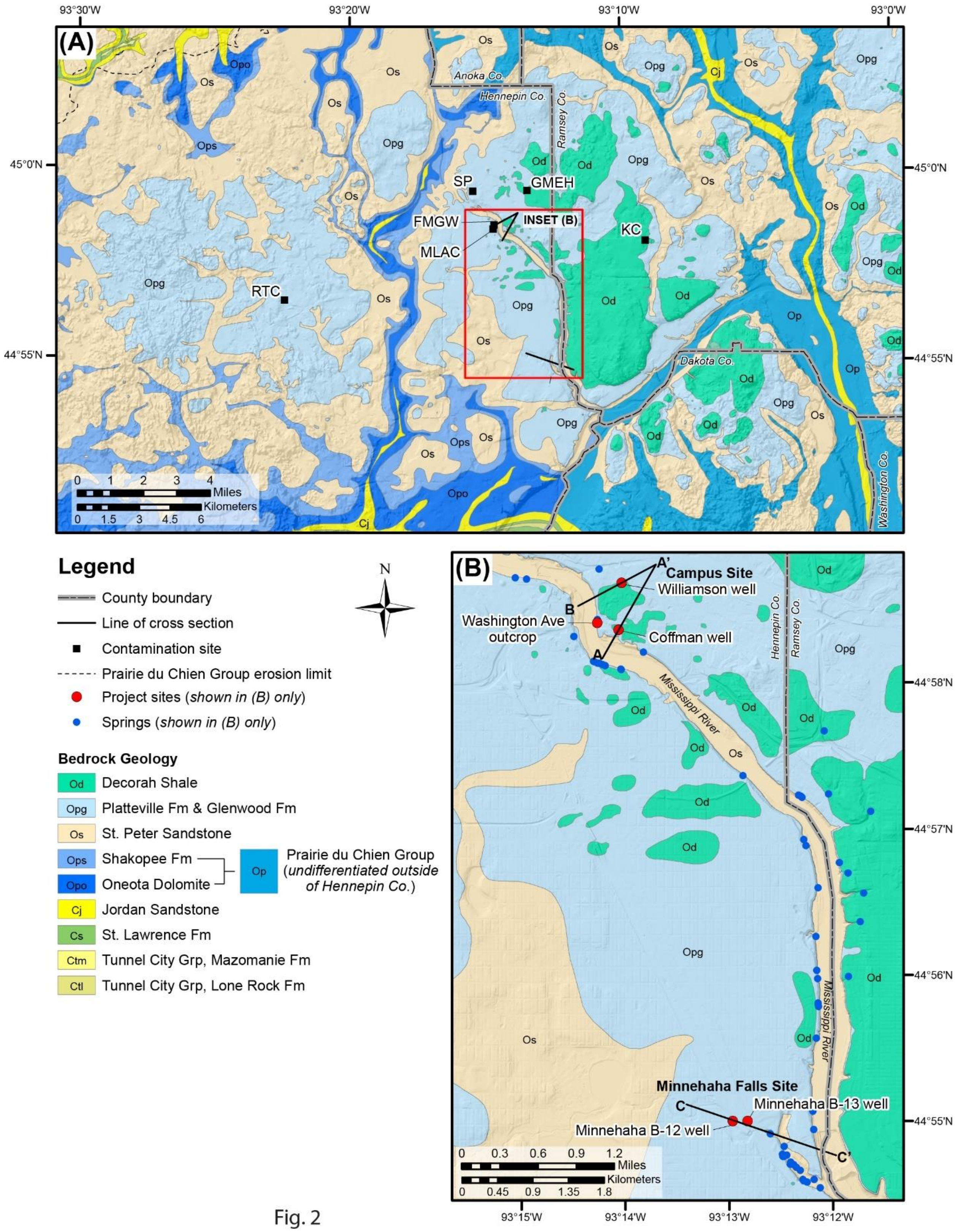
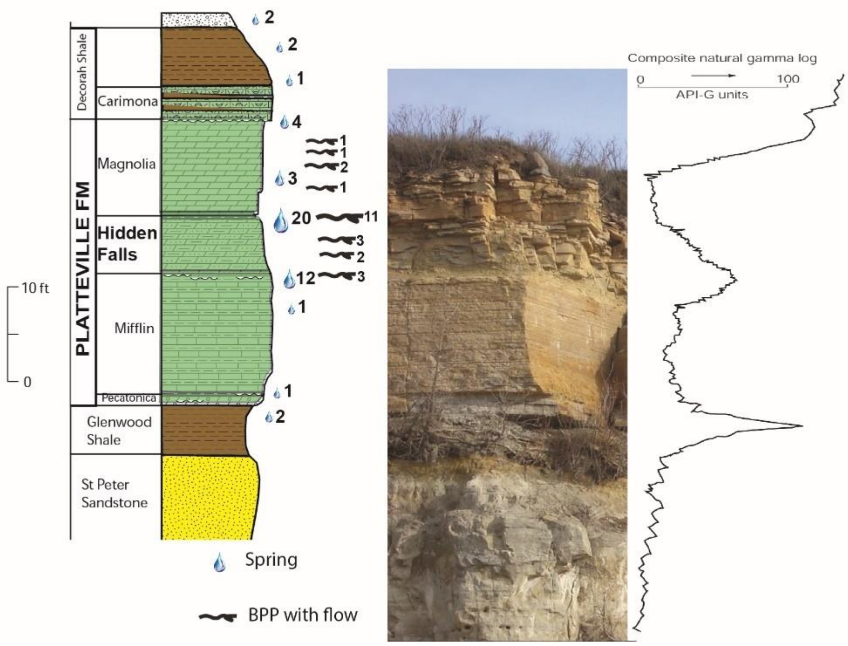
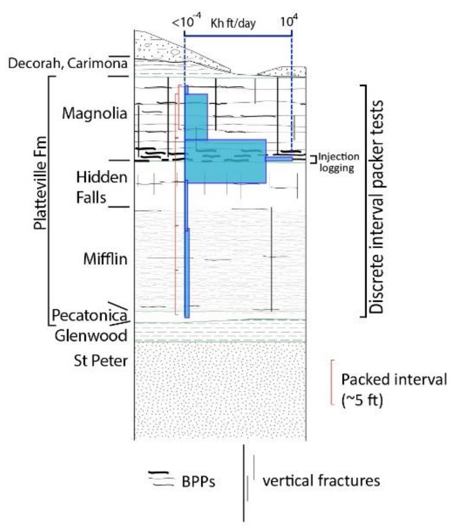

(A)
93°30'W
93°20'W
93°10'W
93°0'W
45°0'N
44°55'N
Anoka Co.
Hennepin Co.
Ramsey Co.
Dakota Co.
Washington Co.
SP
GMEH
FMGW
MLAC
INSET (B)
KC
RTC
Os
Opg
Od
Ops
Opo
Op
Cj
0 1 2 3 4
Miles
Kilometers
0 1.5 3 4.5 6
Legend
County boundary
Line of cross section
Contamination site
Prairie du Chien Group erosion limit
Project sites (shown in (B) only)
Springs (shown in (B) only)
Bedrock Geology
Od Decorah Shale
Opg Platteville Fm & Glenwood Fm
Os St. Peter Sandstone
Ops Shakopee Fm
Opo Oneota Dolomite
Op Prairie du Chien Group (undifferentiated outside of Hennepin Co.)
Cj Jordan Sandstone
Cs St. Lawrence Fm
Ctm Tunnel City Grp, Mazomanie Fm
Ctl Tunnel City Grp, Lone Rock Fm
N
(B)
A'
Campus Site
Williamson well
B
Washington Ave outcrop
Coffman well
A
Mississippi River
Hennepin Co.
Ramsey Co.
Minnehaha Falls Site
C
Minnehaha B-13 well
Minnehaha B-12 well
C'
0 0.3 0.6 0.9 1.2
Miles
Kilometers
0 0.45 0.9 1.35 1.8
44°58'N
44°57'N
44°56'N
44°55'N
93°15'W
93°14'W
93°13'W
93°12'W

Fig. 2



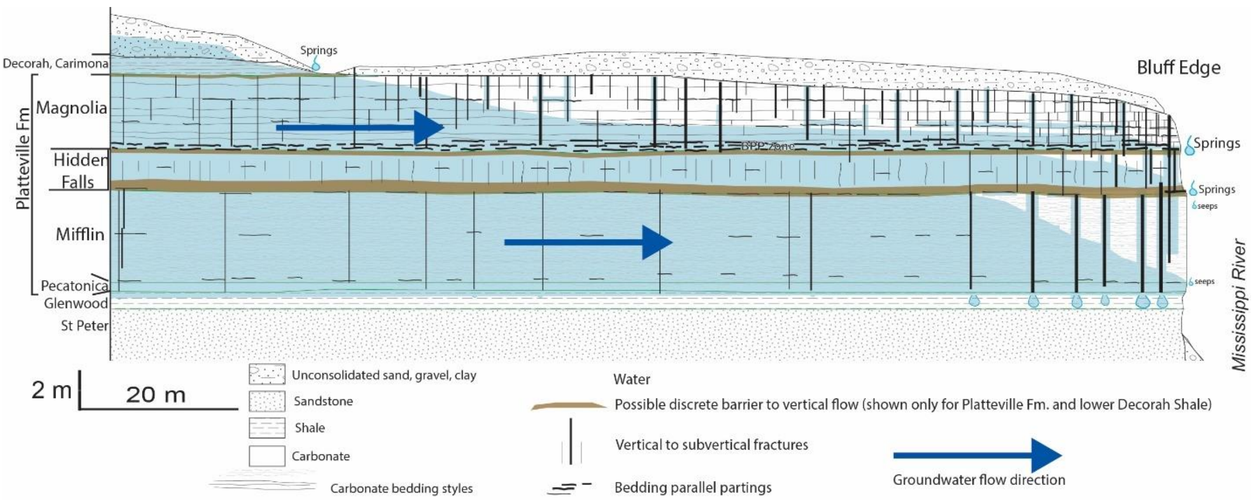
Decorah Shale
Carimona
Magnolia
PLATTEVILLE FM
Hidden Falls
Mifflin
Pecatonica
Glenwood Shale
St Peter Sandstone
10 ft
0
2
2
1
4
1
1
2
3
1
20
11
3
2
12
3
1
1
2
Spring
BPP with flow
Composite natural gamma log
0
100
API-G units

Fig. 3



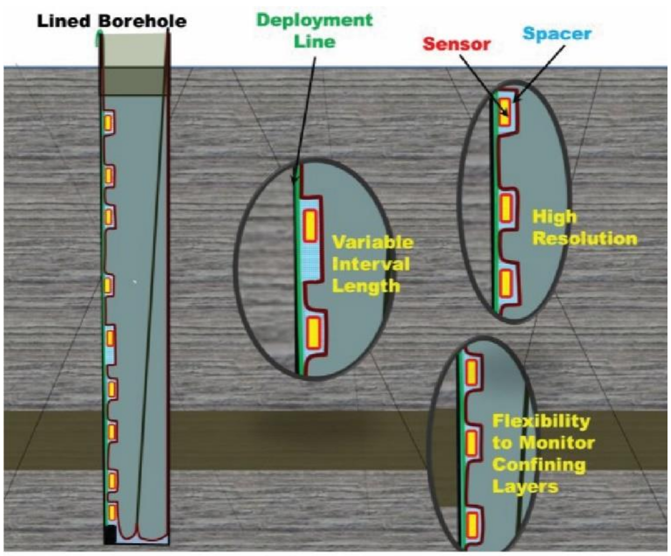
<10^-4
Kh ft/day
10^4
Decorah, Carimona
Magnolia
Platteville Fm
Hidden Falls
Mifflin
Pecatonica
Glenwood
St Peter
Injection logging
Discrete interval packer tests
Packed interval (~5 ft)
BPPs
vertical fractures

Fig. 4



Decorah, Carimona
Springs
Bluff Edge
Platteville Fm
Magnolia
Hidden Falls
Springs
Springs
seeps
Mifflin
Pecatonica
Glenwood
St Peter
seeps
Mississippi River
2 m
20 m
Unconsolidated sand, gravel, clay
Sandstone
Shale
Carbonate
Carbonate bedding styles
Water
Possible discrete barrier to vertical flow (shown only for Platteville Fm. and lower Decorah Shale)
Vertical to subvertical fractures
Bedding parallel partings
Groundwater flow direction

Fig. 5


Lined Borehole
Deployment Line
Sensor
Spacer
Variable Interval Length
High Resolution
Flexibility to Monitor Confining Layers
Fig. 6

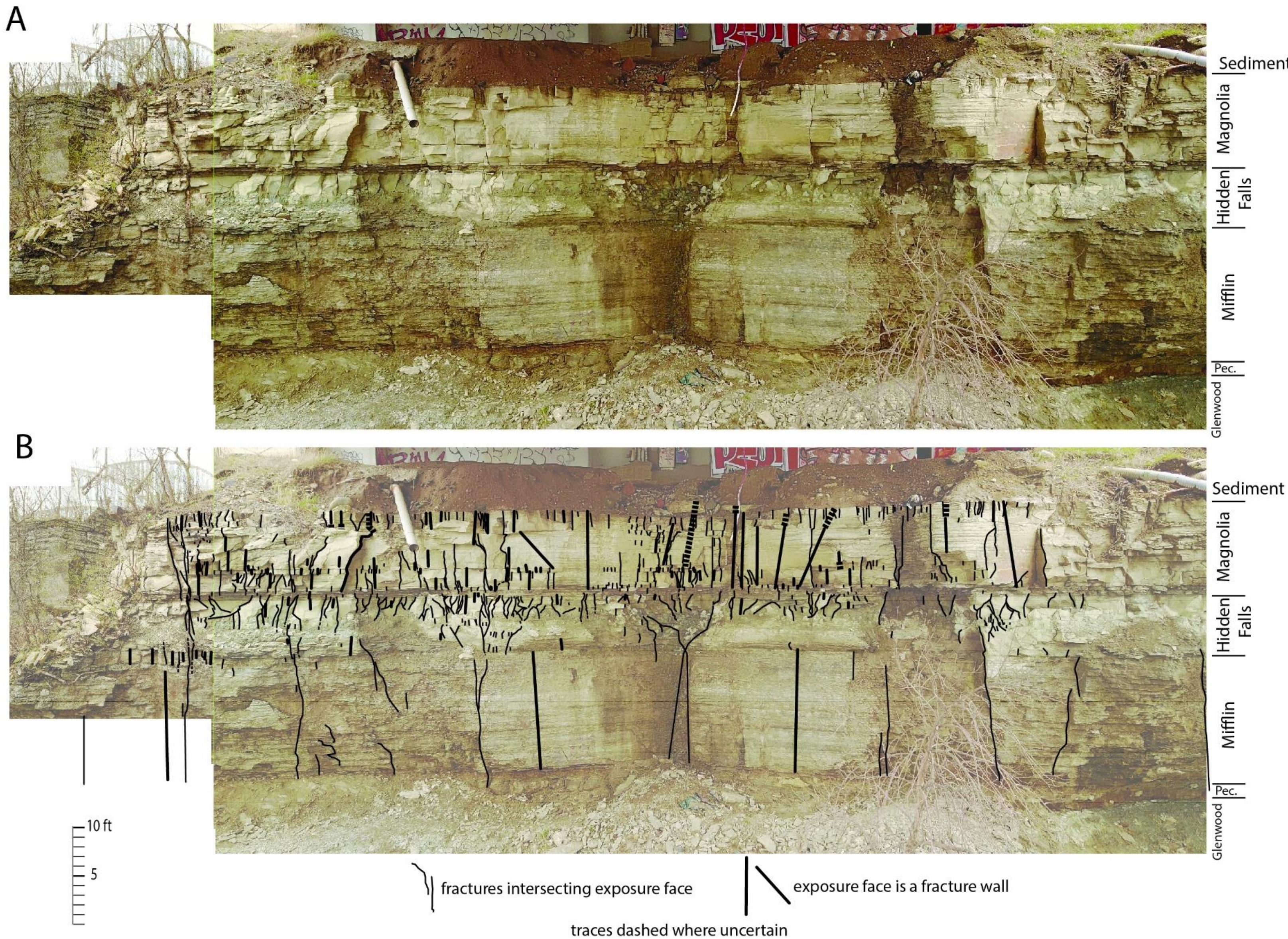

A
B
Sediment
Magnolia
Hidden Falls
Mifflin
Pec.
Glenwood
10 ft
5
fractures intersecting exposure face
exposure face is a fracture wall
traces dashed where uncertain

Fig. 7

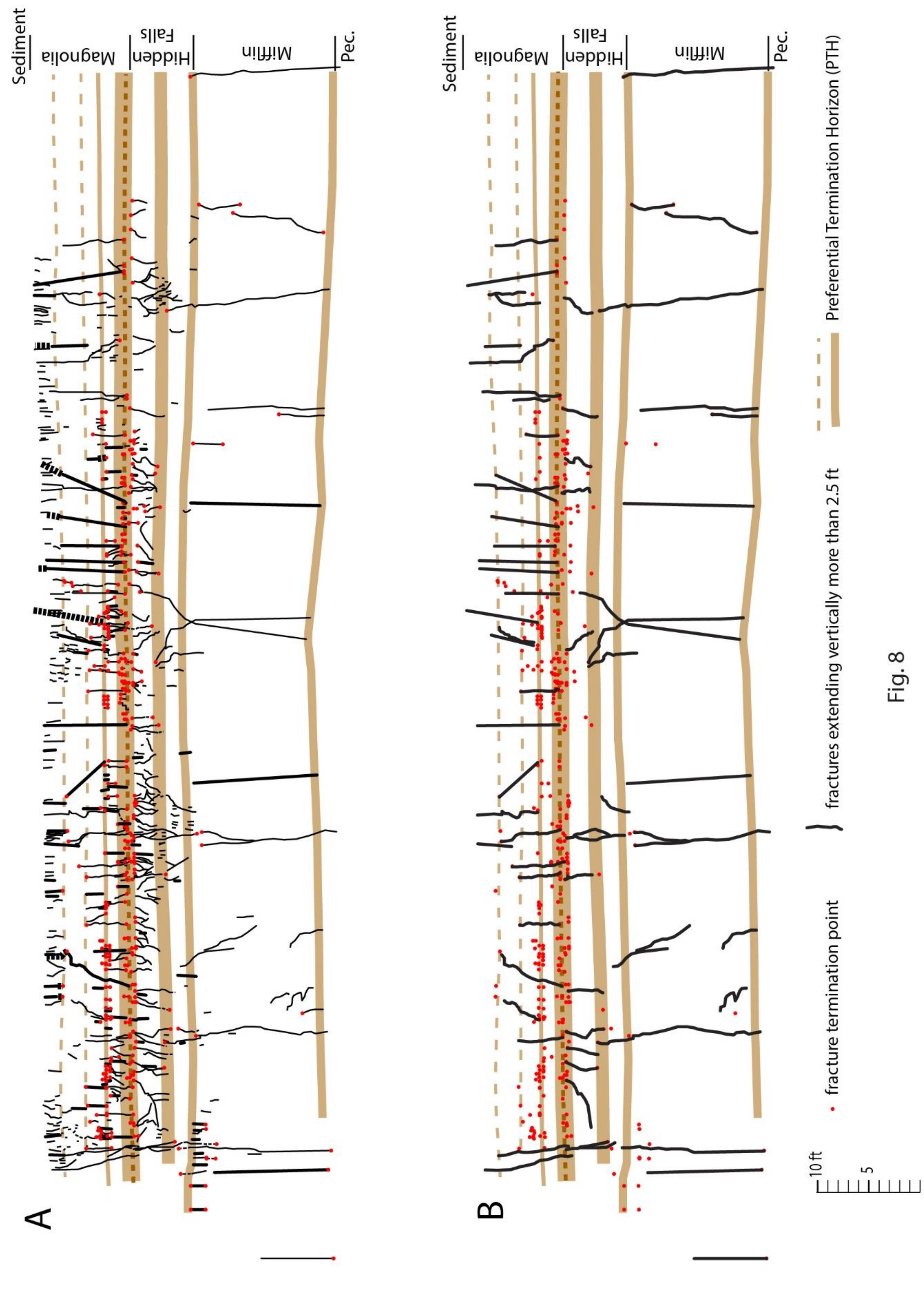

A
B
Sediment
Magnolia
Hidden Falls
Miffin
Pec.
10 ft
5
fracture termination point
fractures extending vertically more than 2.5 ft
Preferential Termination Horizon (PTH)

Fig. 8

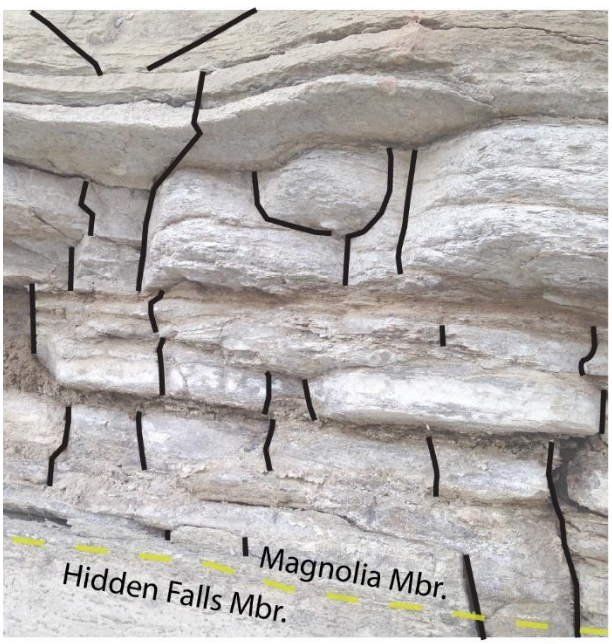
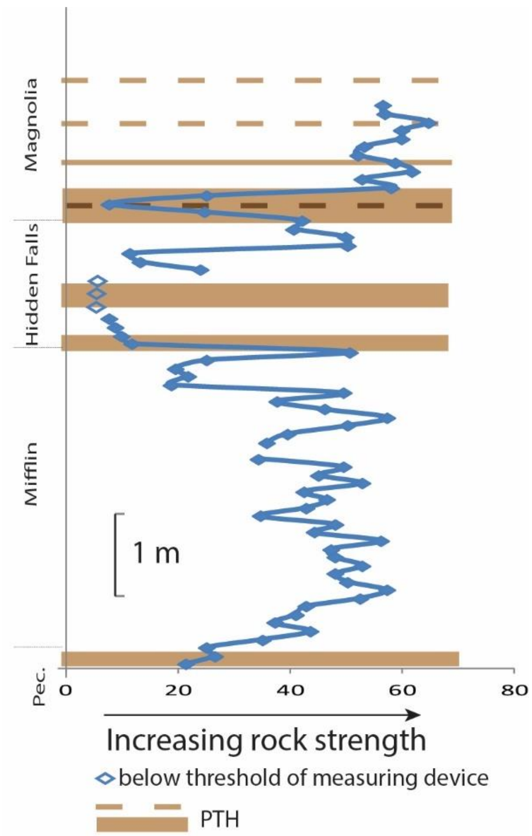


Fig. 9



Magnolia
Hidden Falls
Mifflin
Pec.
1 m
0
20
40
60
80
Increasing rock strength
below threshold of measuring device
PTH

Fig. 10

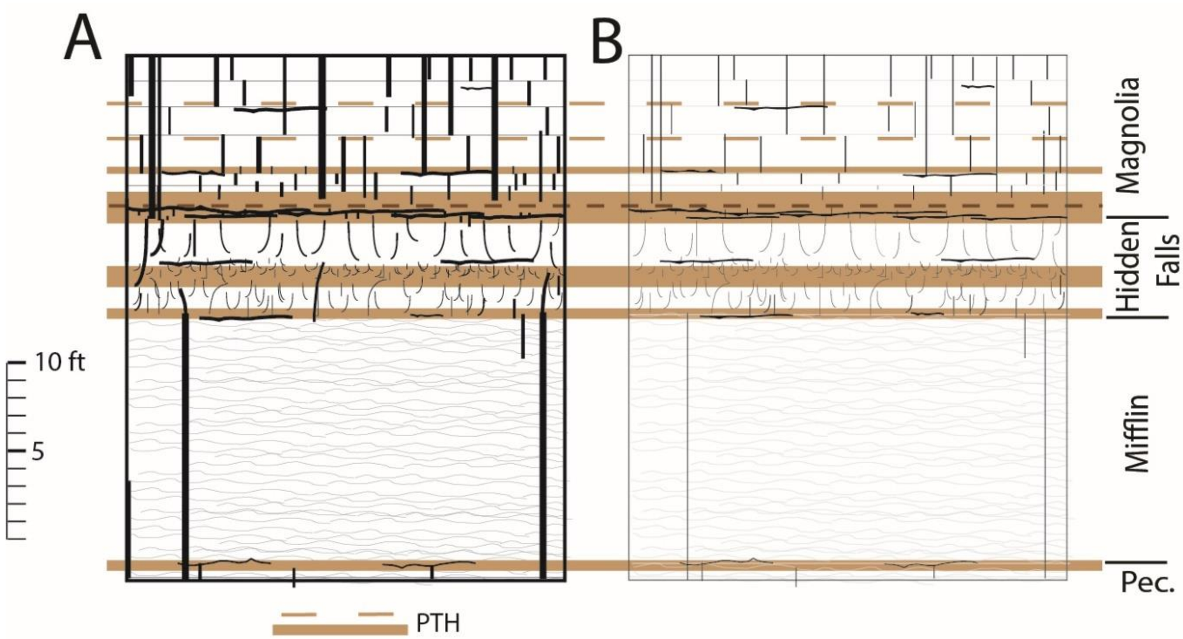


Fig. 11

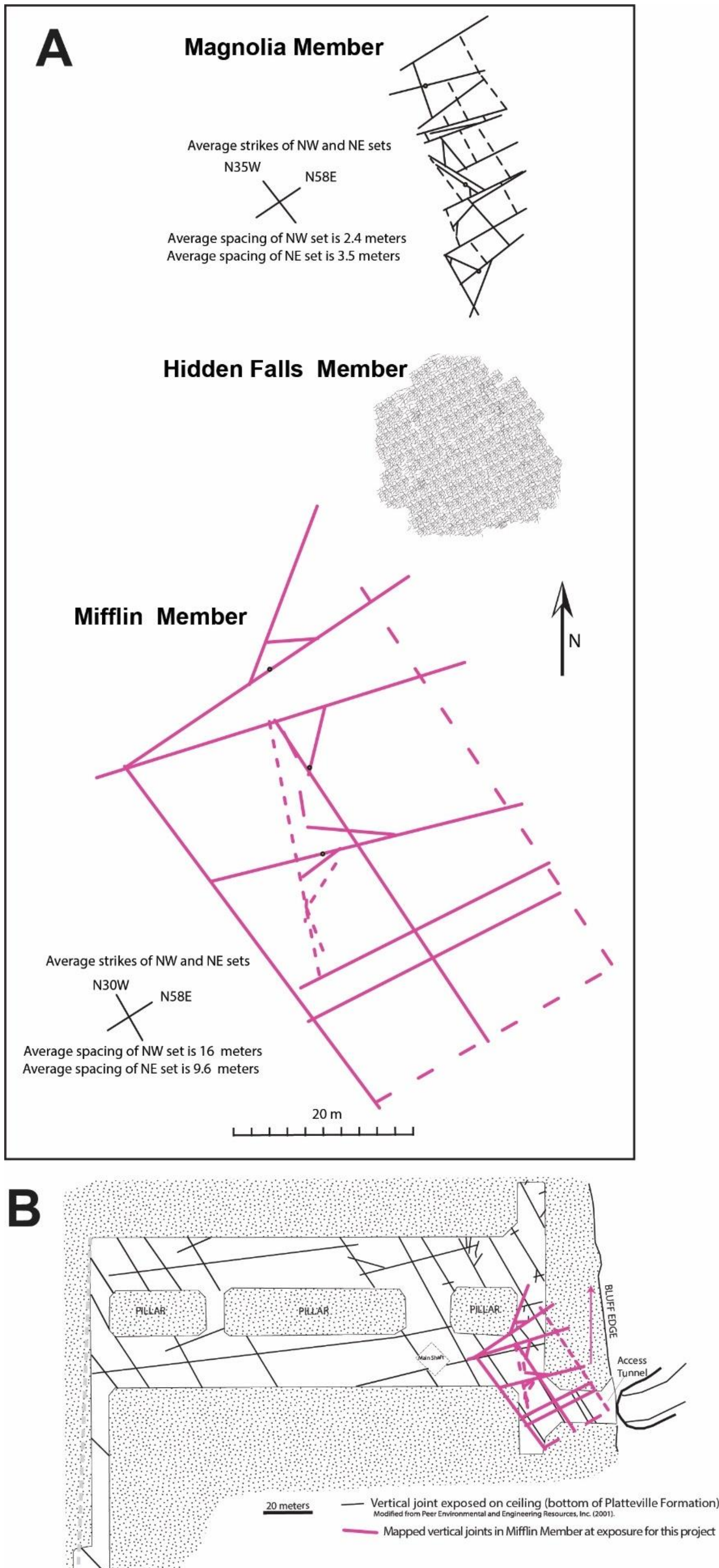
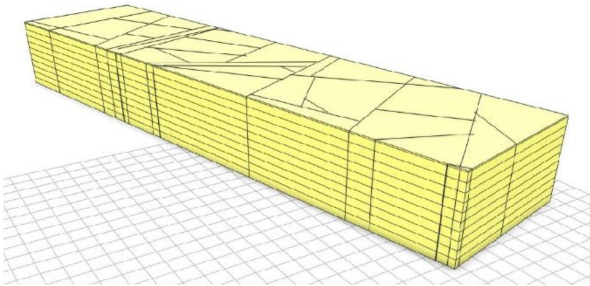
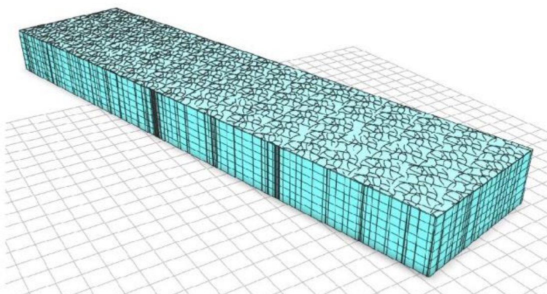

A
Magnolia Member
Average strikes of NW and NE sets
N35W
N58E
Average spacing of NW set is 2.4 meters
Average spacing of NE set is 3.5 meters
Hidden Falls Member
Mifflin Member
N
Average strikes of NW and NE sets
N30W
N58E
Average spacing of NW set is 16 meters
Average spacing of NE set is 9.6 meters
20 m
B
PILLAR
PILLAR
PILLAR
Main Shaft
BLUFF EDGE
Access Tunnel
20 meters
Vertical joint exposed on ceiling (bottom of Platteville Formation)
Modified from Peer Environmental and Engineering Resources, Inc. (2001).
Mapped vertical joints in Mifflin Member at exposure for this project

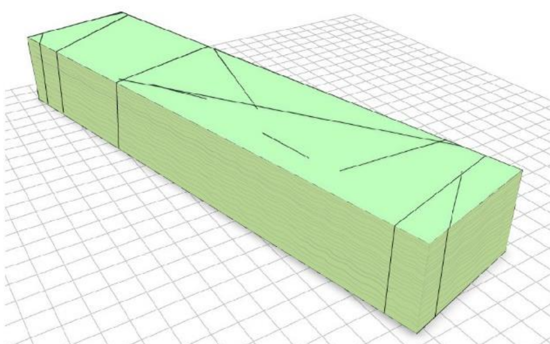
Fig. 12



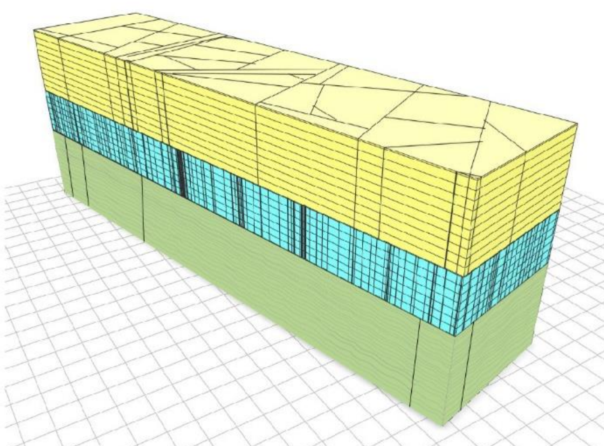
Magnolia Member



Hidden Falls Member



Mifflin Member



All members

Fig. 13

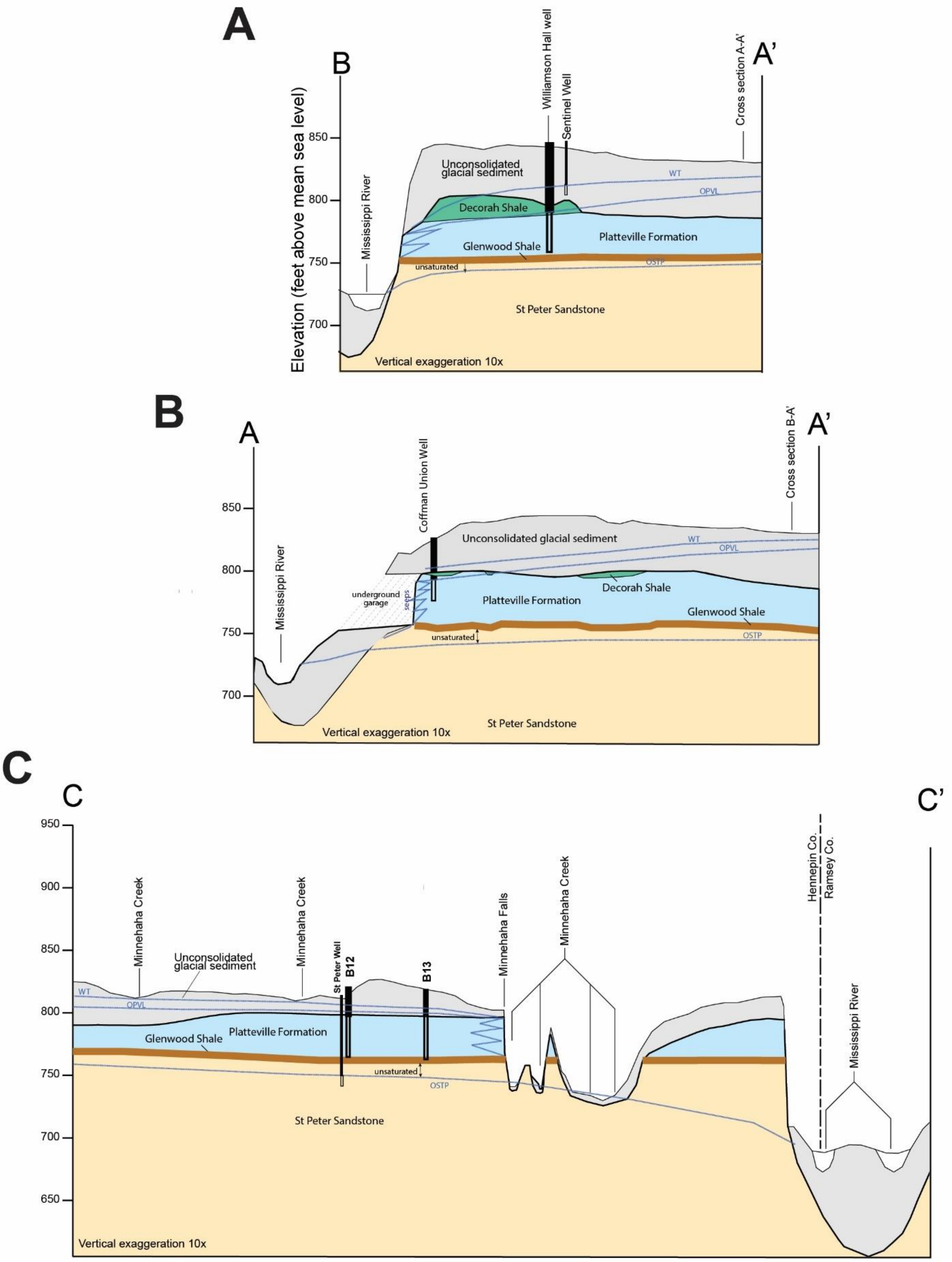
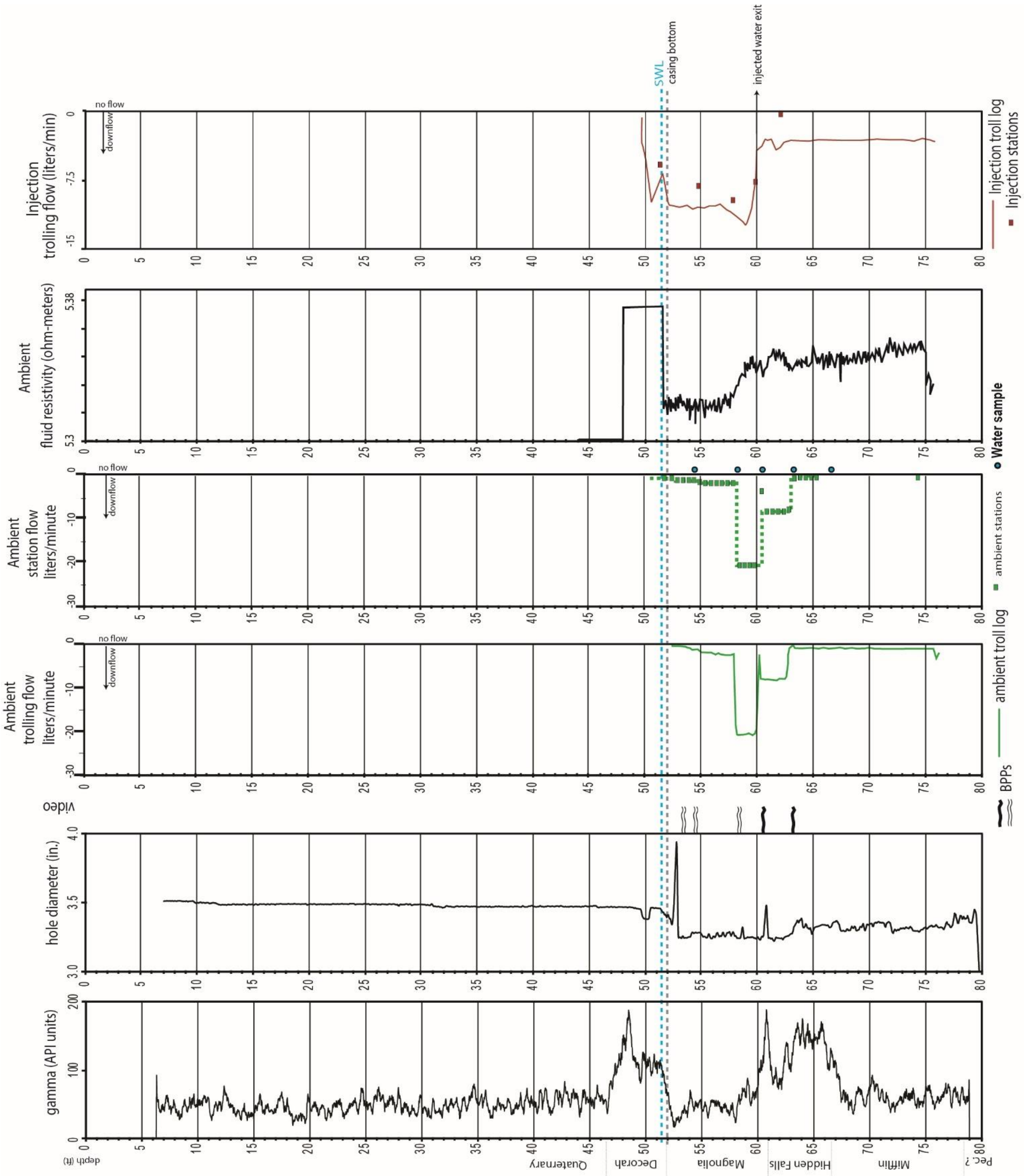

A
B
A'
Elevation (feet above mean sea level)
850
800
750
700
Williamson Hall well
Sentinel Well
Cross section A-A'
Mississippi River
Unconsolidated glacial sediment
WT
OPVL
Decorah Shale
Platteville Formation
Glenwood Shale
unsaturated
OSTP
St Peter Sandstone
Vertical exaggeration 10x
B
A
A'
Coffman Union Well
Cross section B-A'
Mississippi River
Unconsolidated glacial sediment
underground garage
seeps
Decorah Shale
Platteville Formation
Glenwood Shale
unsaturated
OSTP
St Peter Sandstone
Vertical exaggeration 10x
C
C
C'
950
900
650
Minnehaha Creek
Minnehaha Creek
Unconsolidated glacial sediment
St Peter Well
B12
B13
Minnehaha Falls
Minnehaha Creek
Hennepin Co.
Ramsey Co.
Mississippi River
WT
OPVL
Glenwood Shale
Platteville Formation
unsaturated
OSTP
St Peter Sandstone
Vertical exaggeration 10x

Fig. 14



Injection trolling flow (liters/min)
no flow
downflow
SWL
casing bottom
injected water exit
Injection troll log
Injection stations
Ambient fluid resistivity (ohm-meters)
Water sample
Ambient station flow liters/minute
ambient stations
Ambient trolling flow liters/minute
ambient troll log
video
BPPs
hole diameter (in.)
gamma (API units)
depth (ft)
Quaternary
Decorah
Magnolia
Hidden Falls
Mifflin
Pec. ?

Fig. 15

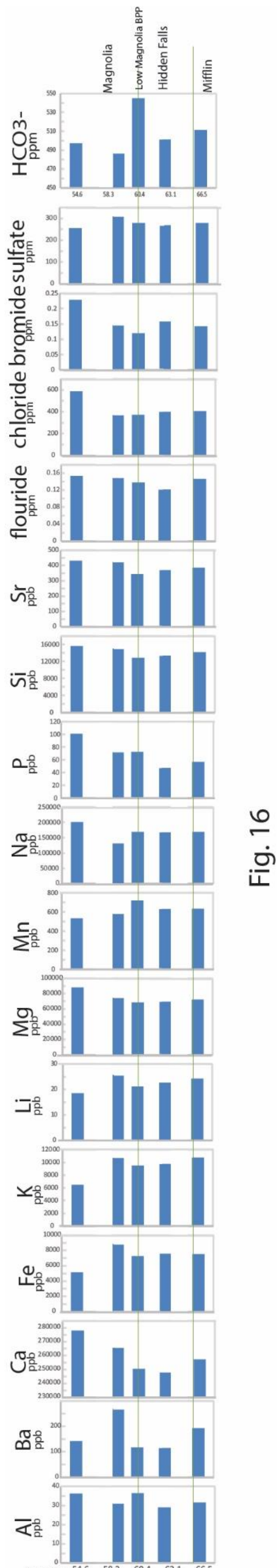

Magnolia
Low Magnolia BPP
Hidden Falls
Mifflin
HCO3- ppm
sulfate ppm
bromide ppm
chloride ppm
flouride ppm
Sr ppb
Si ppb
P ppb
Na ppb
Mn ppb
Mg ppb
Li ppb
K ppb
Fe ppb
Ca ppb
Ba ppb
Al ppb
depth (ft)
54.6
58.3
60.4
63.1
66.5

Fig. 16

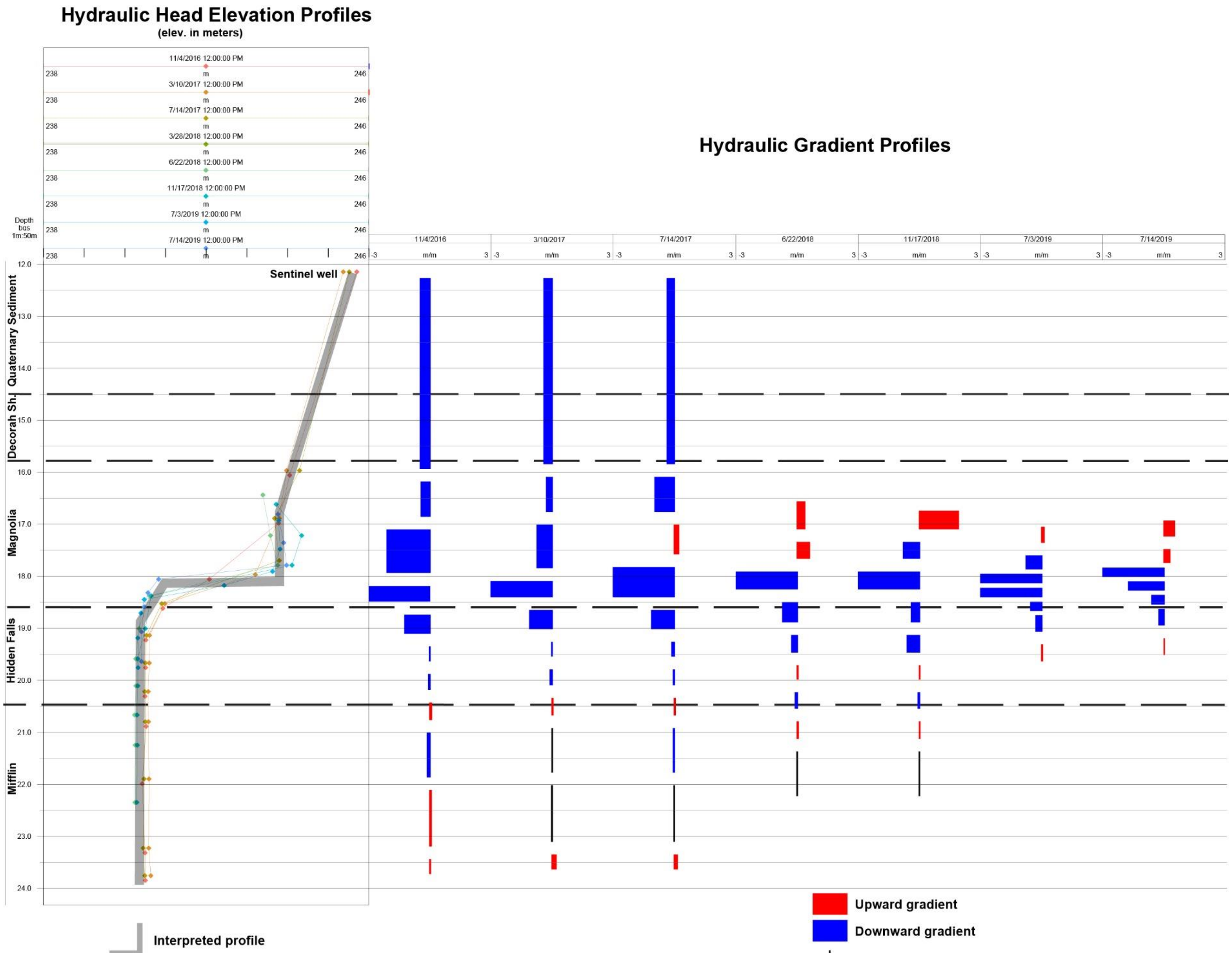

Hydraulic Head Elevation Profiles
(elev. in meters)
11/4/2016 12:00:00 PM
3/10/2017 12:00:00 PM
7/14/2017 12:00:00 PM
3/28/2018 12:00:00 PM
6/22/2018 12:00:00 PM
11/17/2018 12:00:00 PM
7/3/2019 12:00:00 PM
7/14/2019 12:00:00 PM
m
238
246
Depth bgs 1m:50m
Sentinel well
Quaternary Sediment
Decorah Sh.
Magnolia
Hidden Falls
Mifflin
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
23.0
24.0
Interpreted profile
Hydraulic Gradient Profiles
11/4/2016
3/10/2017
7/14/2017
6/22/2018
11/17/2018
7/3/2019
7/14/2019
-3
m/m
3
Upward gradient
Downward gradient
no measurable gradient

Fig. 17

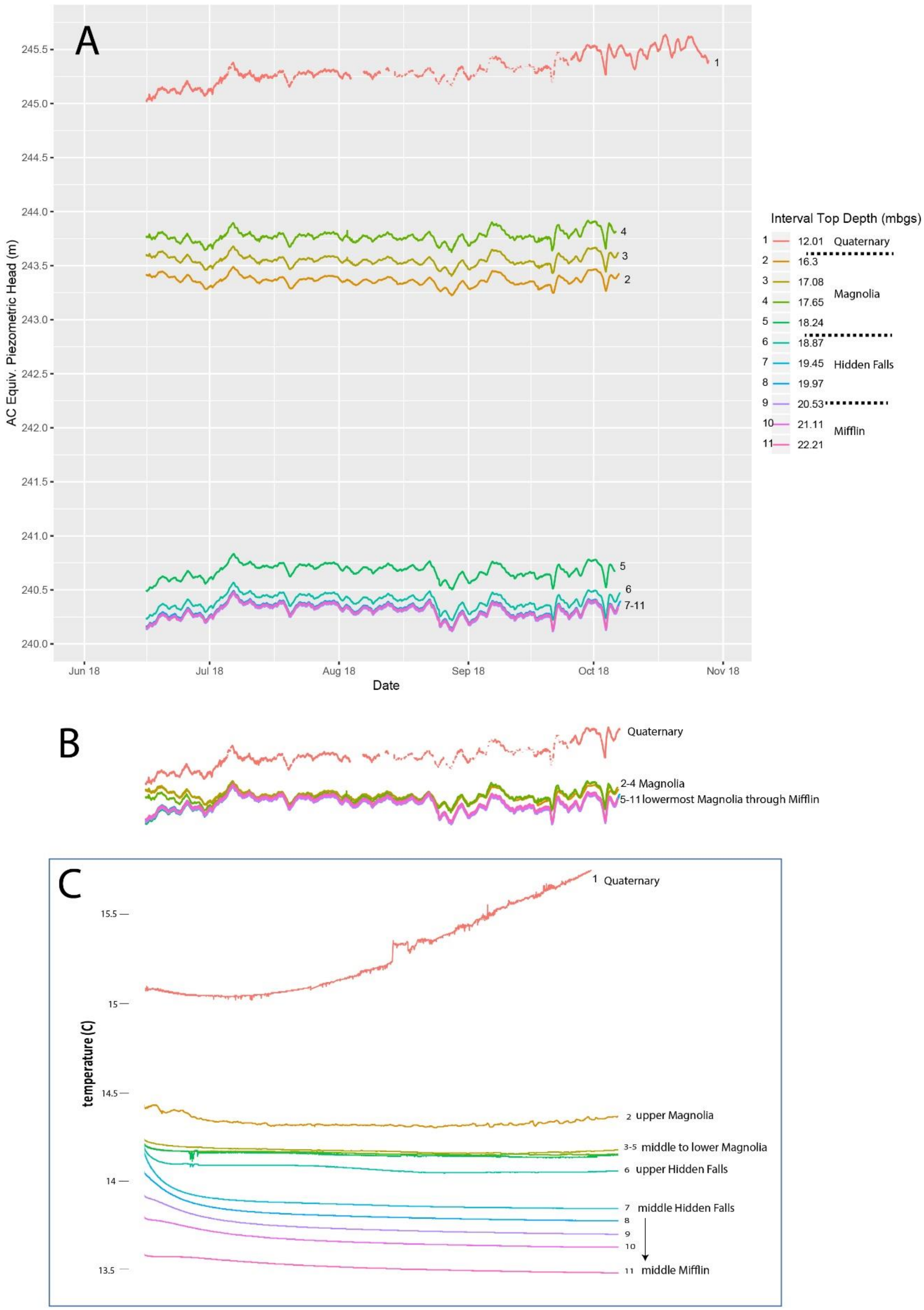

A
245.5
245.0
244.5
244.0
243.5
243.0
242.5
242.0
241.5
241.0
240.5
240.0
AC Equiv. Piezometric Head (m)
Jun 18
Jul 18
Aug 18
Sep 18
Oct 18
Nov 18
Date
1
4
3
2
5
6
7-11
Interval Top Depth (mbgs)
1 12.01 Quaternary
2 16.3
3 17.08
4 17.65 Magnolia
5 18.24
6 18.87
7 19.45 Hidden Falls
8 19.97
9 20.53
10 21.11 Mifflin
11 22.21
B
Quaternary
2-4 Magnolia
5-11 lowermost Magnolia through Mifflin
C
15.5
15
14.5
14
13.5
temperature (C)
1 Quaternary
2 upper Magnolia
3-5 middle to lower Magnolia
6 upper Hidden Falls
7 middle Hidden Falls
8
9
10
11 middle Mifflin

Fig. 18

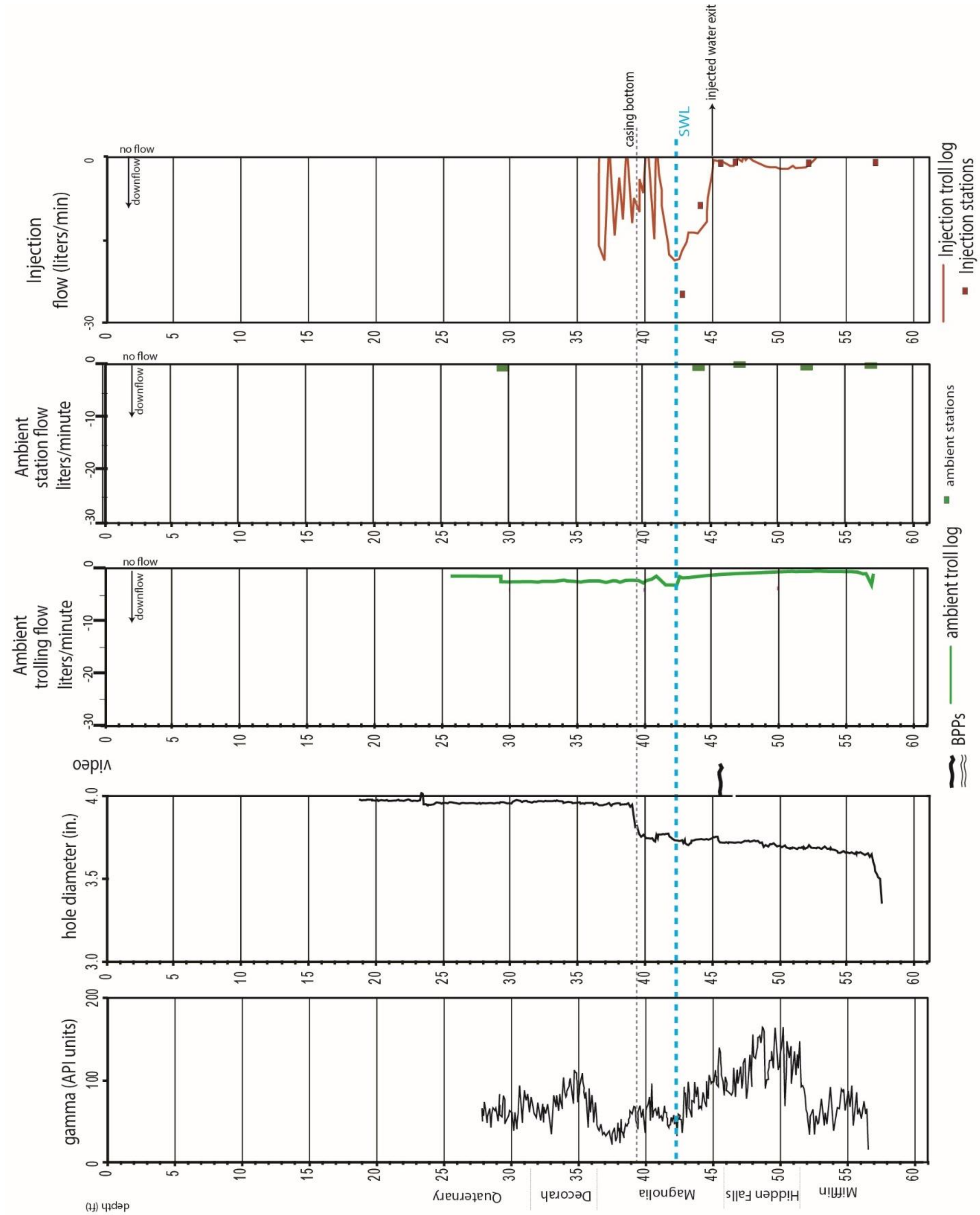
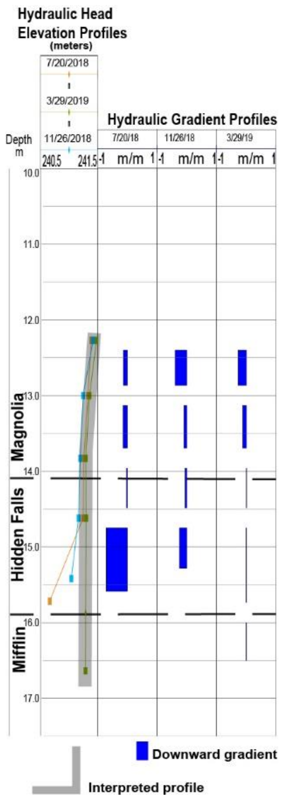

gamma (API units)
hole diameter (in.)
video
Ambient trolling flow liters/minute
Ambient station flow liters/minute
Injection flow (liters/min)
no flow
downflow
casing bottom
SWL
injected water exit
depth (ft)
Quaternary
Decorah
Magnolia
Hidden Falls
Miffiin
BPPs
ambient troll log
ambient stations
Injection troll log
Injection stations

Fig. 19



Hydraulic Head
Elevation Profiles
(meters)
7/20/2018
3/29/2019
11/26/2018
Depth
m
240.5
241.5
Hydraulic Gradient Profiles
7/20/18
11/26/18
3/29/19
-1 m/m 1
-1 m/m 1
-1 m/m 1
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
Magnolia
Hidden Falls
Mifflin
Downward gradient
Interpreted profile

Fig. 20

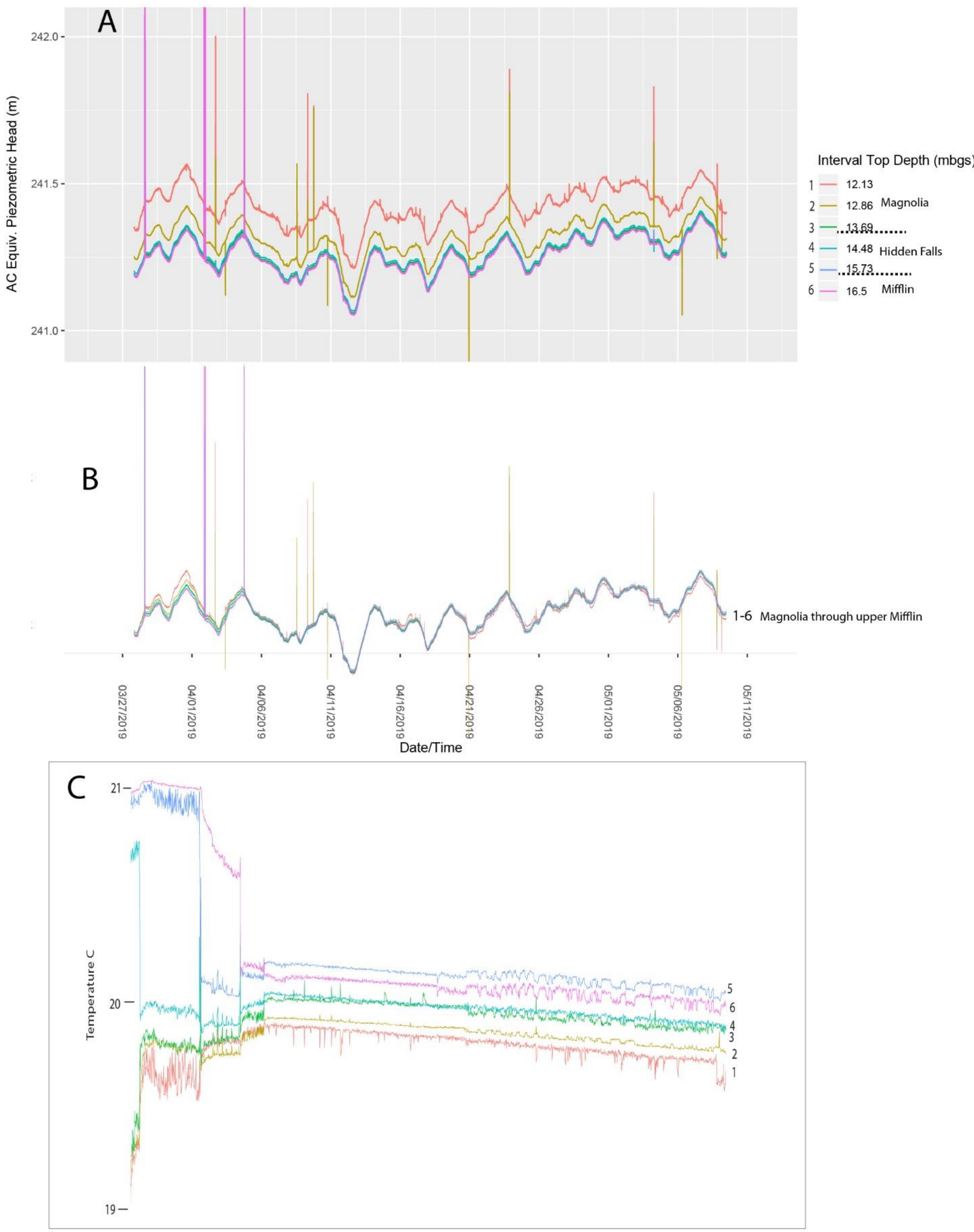
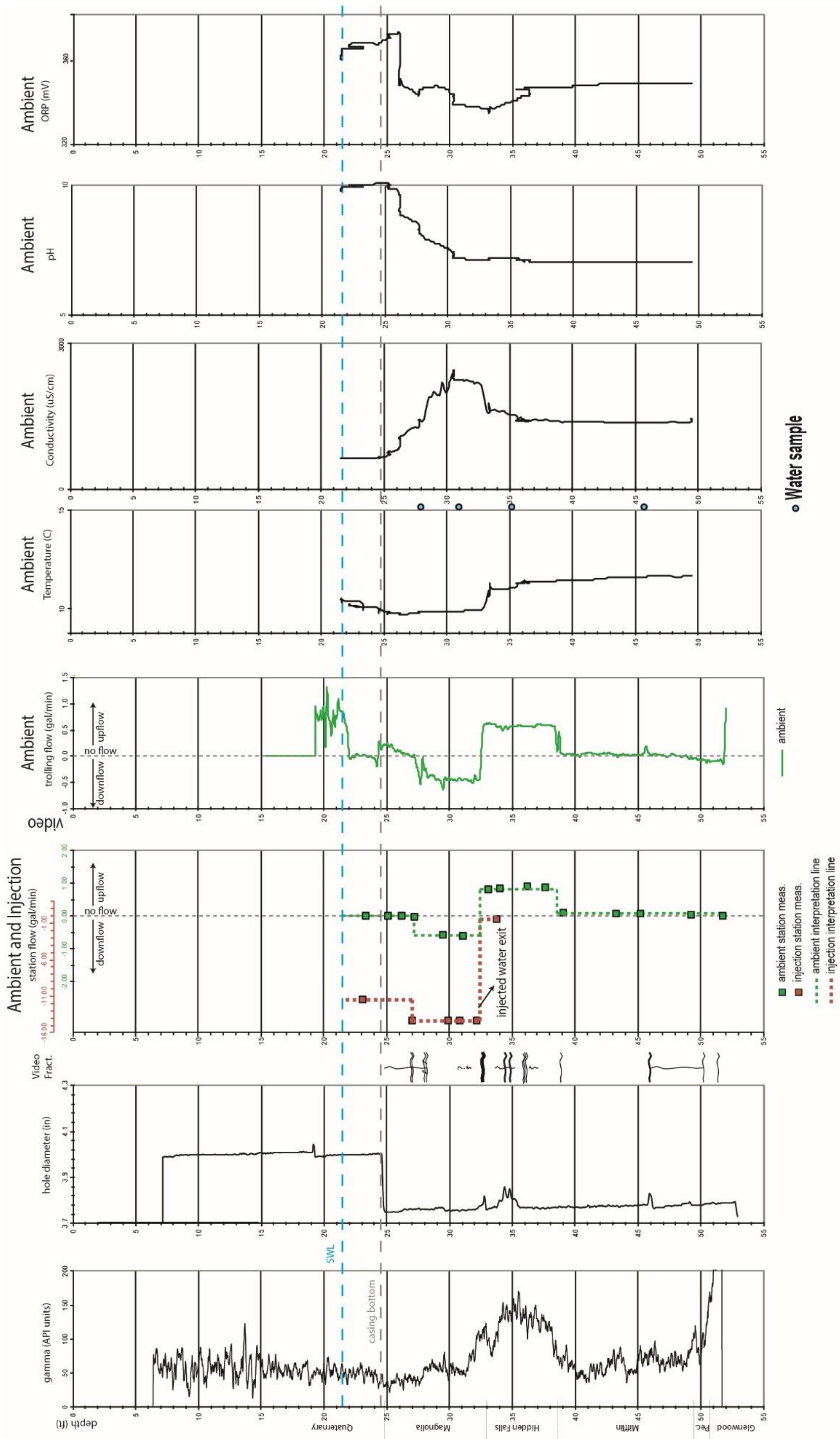

A
B
C
AC Equiv. Piezometric Head (m)
242.0
241.5
241.0
Interval Top Depth (mbgs)
1 12.13
2 12.86 Magnolia
3 13.69
4 14.48 Hidden Falls
5 15.73
6 16.5 Mifflin
1-6 Magnolia through upper Mifflin
03/27/2019
04/01/2019
04/06/2019
04/11/2019
04/16/2019
04/21/2019
04/26/2019
05/01/2019
05/06/2019
05/11/2019
Date/Time
Temperature C
21
20
19
5
6
4
3
2
1

Fig. 21



depth (ft)
gamma (API units)
hole diameter (in)
Video Fract.
Ambient and Injection
station flow (gal/min)
downflow
no flow
upflow
injected water exit
ambient station meas.
injection station meas.
ambient interpretation line
injection interpretation line
video
Ambient
trolling flow (gal/min)
ambient
Temperature (C)
Conductivity (uS/cm)
pH
ORP (mV)
Water sample
SWL
casing bottom
Quaternary
Magnolia
Hidden Falls
Mifflin
Pec.
Glenwood

Fig. 22

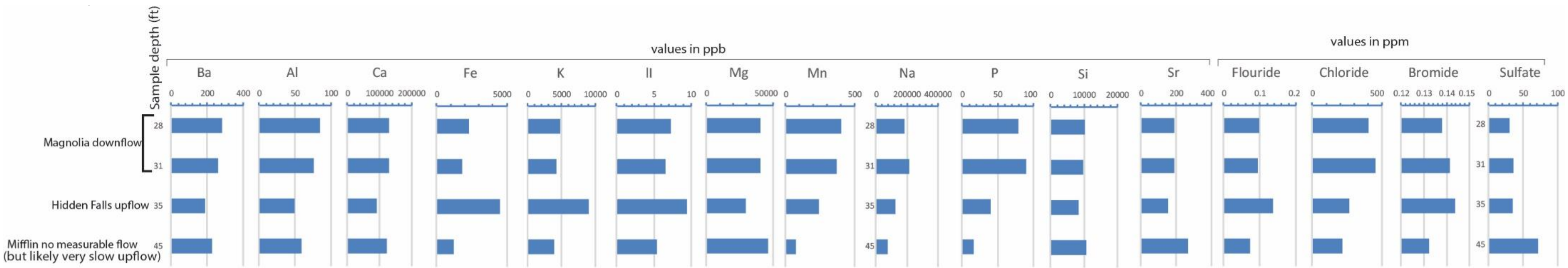

Sample depth (ft)
values in ppb
values in ppm
Ba
Al
Ca
Fe
K
Il
Mg
Mn
Na
P
Si
Sr
Flouride
Chloride
Bromide
Sulfate
Magnolia downflow
Hidden Falls upflow
Mifflin no measurable flow
(but likely very slow upflow)
28
31
35
45

Fig. 23

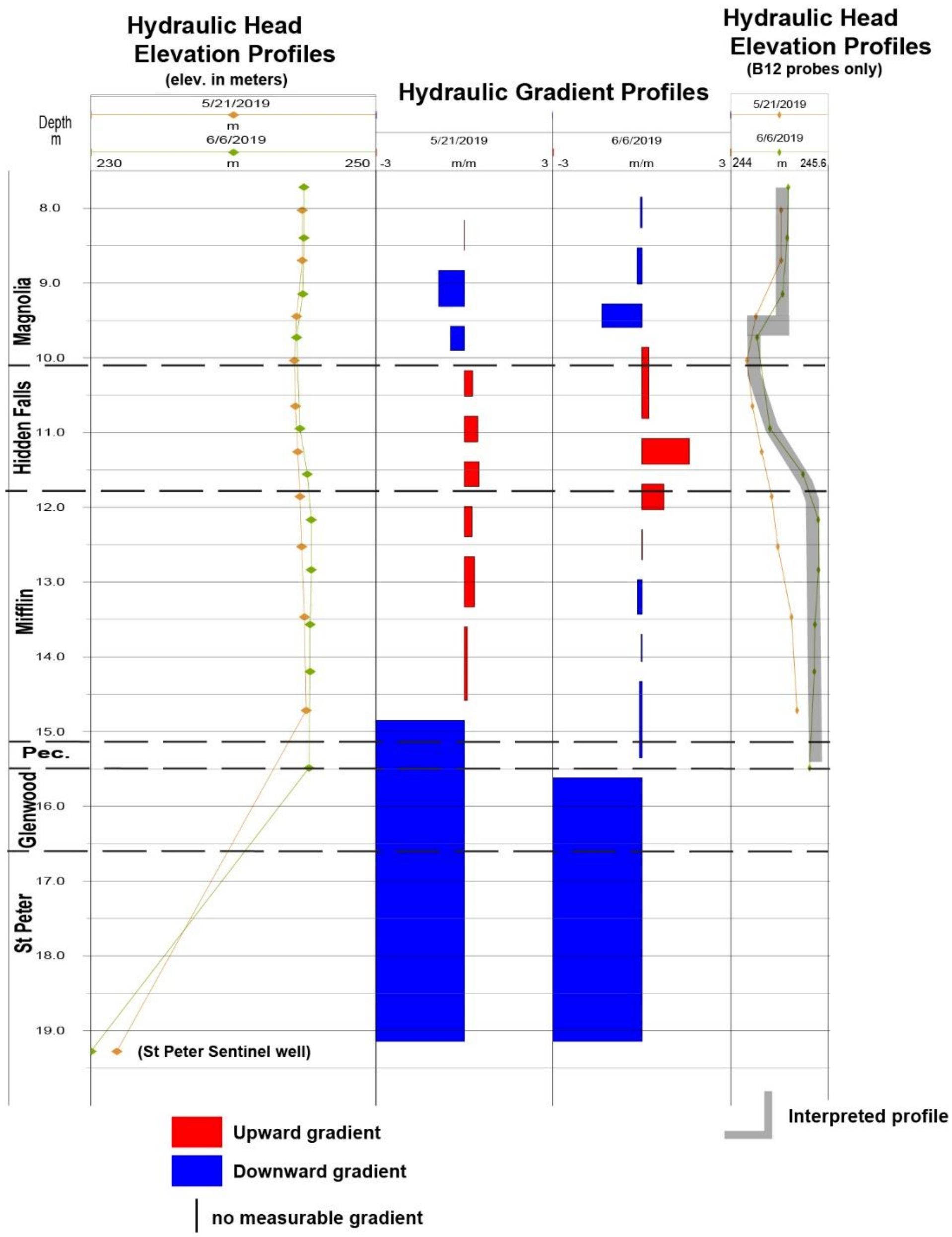

Hydraulic Head Elevation Profiles
(elev. in meters)
Hydraulic Gradient Profiles
Hydraulic Head Elevation Profiles
(B12 probes only)
Depth m
5/21/2019
6/6/2019
230
m
250
-3
m/m
3
244
245.6
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
Magnolia
Hidden Falls
Mifflin
Pec.
Glenwood
St Peter
(St Peter Sentinel well)
Upward gradient
Downward gradient
no measurable gradient
Interpreted profile

Fig. 24

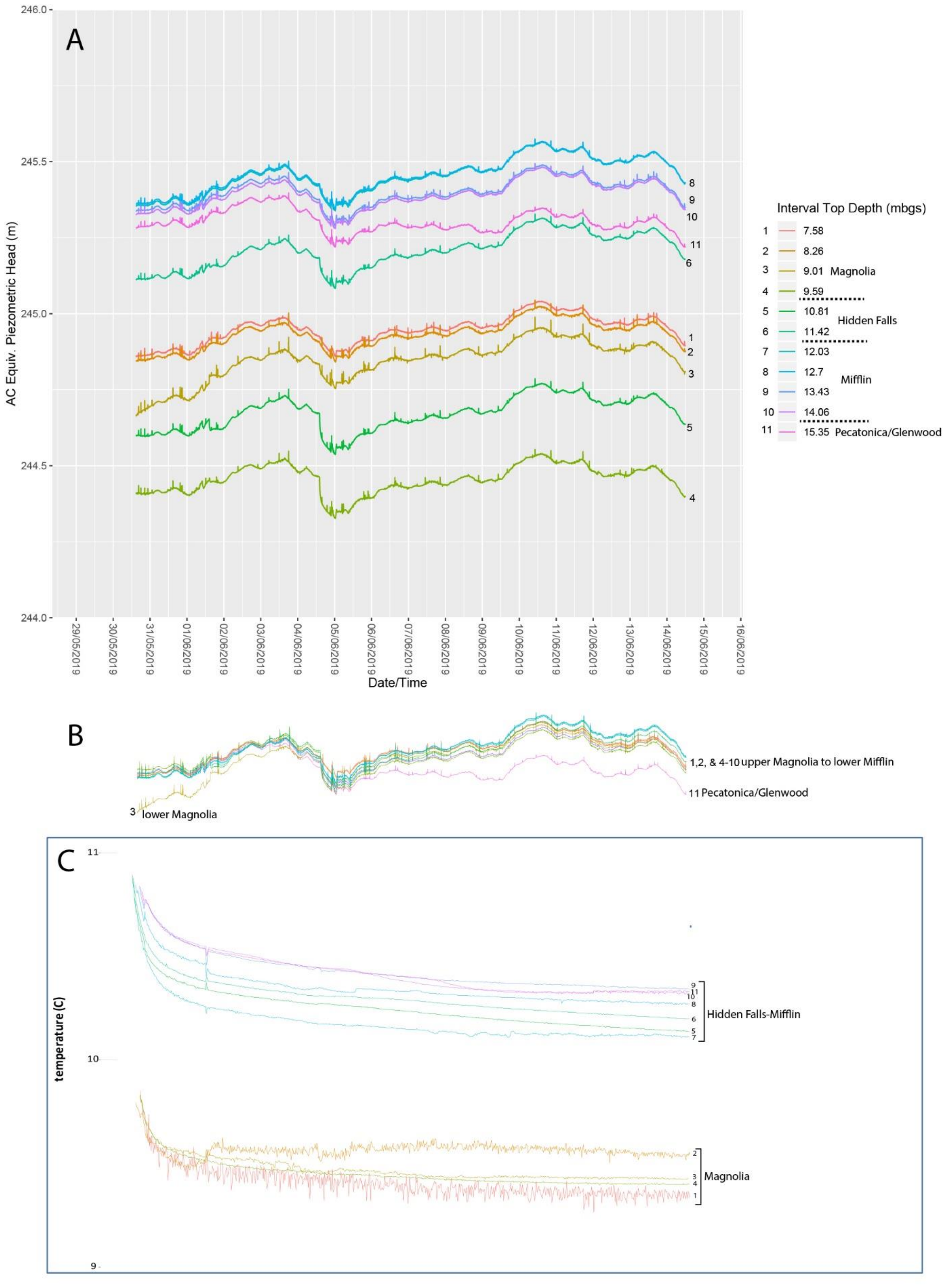
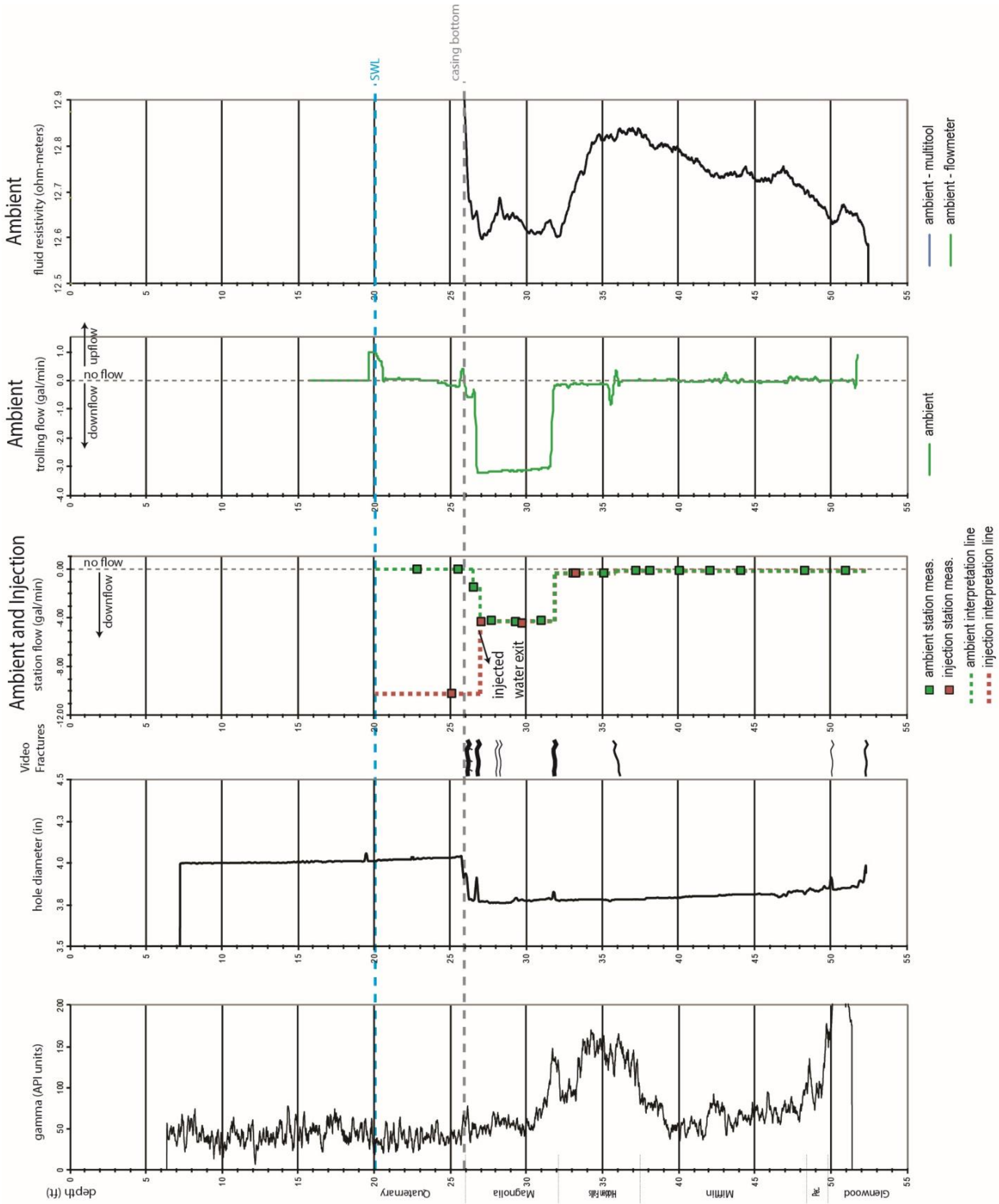
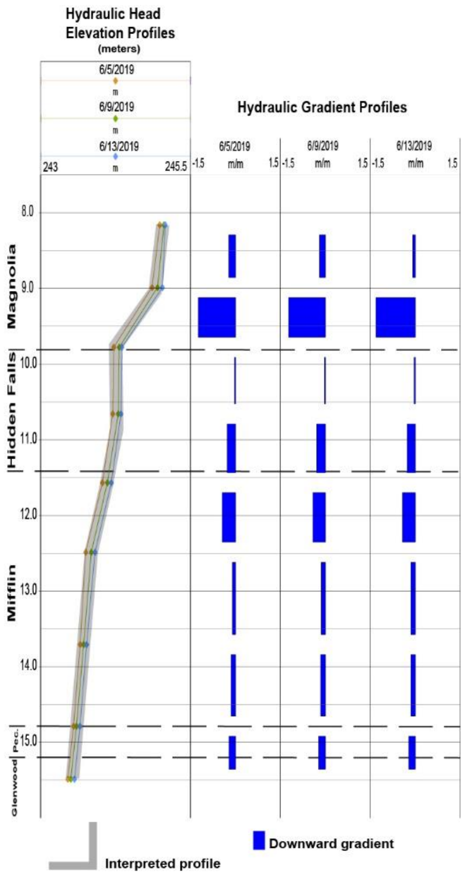

A
AC Equiv. Piezometric Head (m)
Date/Time
Interval Top Depth (mbgs)
1 7.58
2 8.26
3 9.01 Magnolia
4 9.59
5 10.81
6 11.42 Hidden Falls
7 12.03
8 12.7
9 13.43 Mifflin
10 14.06
11 15.35 Pecatonica/Glenwood
B
1,2, & 4-10 upper Magnolia to lower Mifflin
11 Pecatonica/Glenwood
3 lower Magnolia
C
temperature (C)
Hidden Falls-Mifflin
Magnolia

Fig. 25



Ambient
fluid resistivity (ohm-meters)
ambient - multitool
ambient - flowmeter
Ambient
trolling flow (gal/min)
upflow
no flow
downflow
ambient
Ambient and Injection
station flow (gal/min)
no flow
downflow
injected water exit
ambient station meas.
injection station meas.
ambient interpretation line
injection interpretation line
Video Fractures
hole diameter (in)
gamma (API units)
depth (ft)
SWL
casing bottom
Quaternary
Magnolia
Hidden Falls
Mifflin
Glenwood

Fig. 26



Hydraulic Head
Elevation Profiles
(meters)
6/5/2019
m
6/9/2019
m
6/13/2019
243
m
245.5
Hydraulic Gradient Profiles
6/5/2019
-1.5
m/m
1.5
6/9/2019
-1.5
m/m
1.5
6/13/2019
-1.5
m/m
1.5
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
Magnolia
Hidden Falls
Mifflin
Pec.
Glenwood
Downward gradient
Interpreted profile

Fig. 27

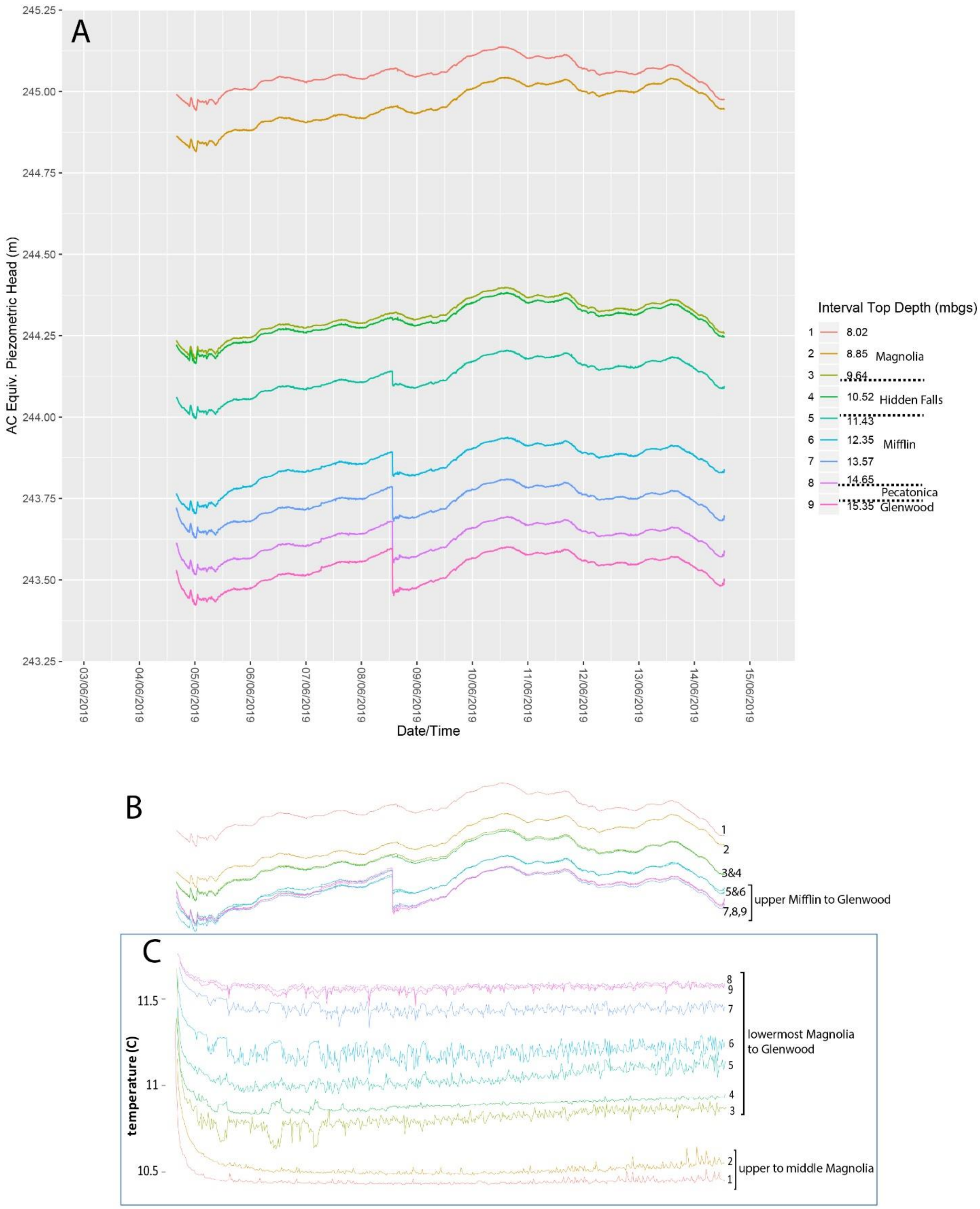
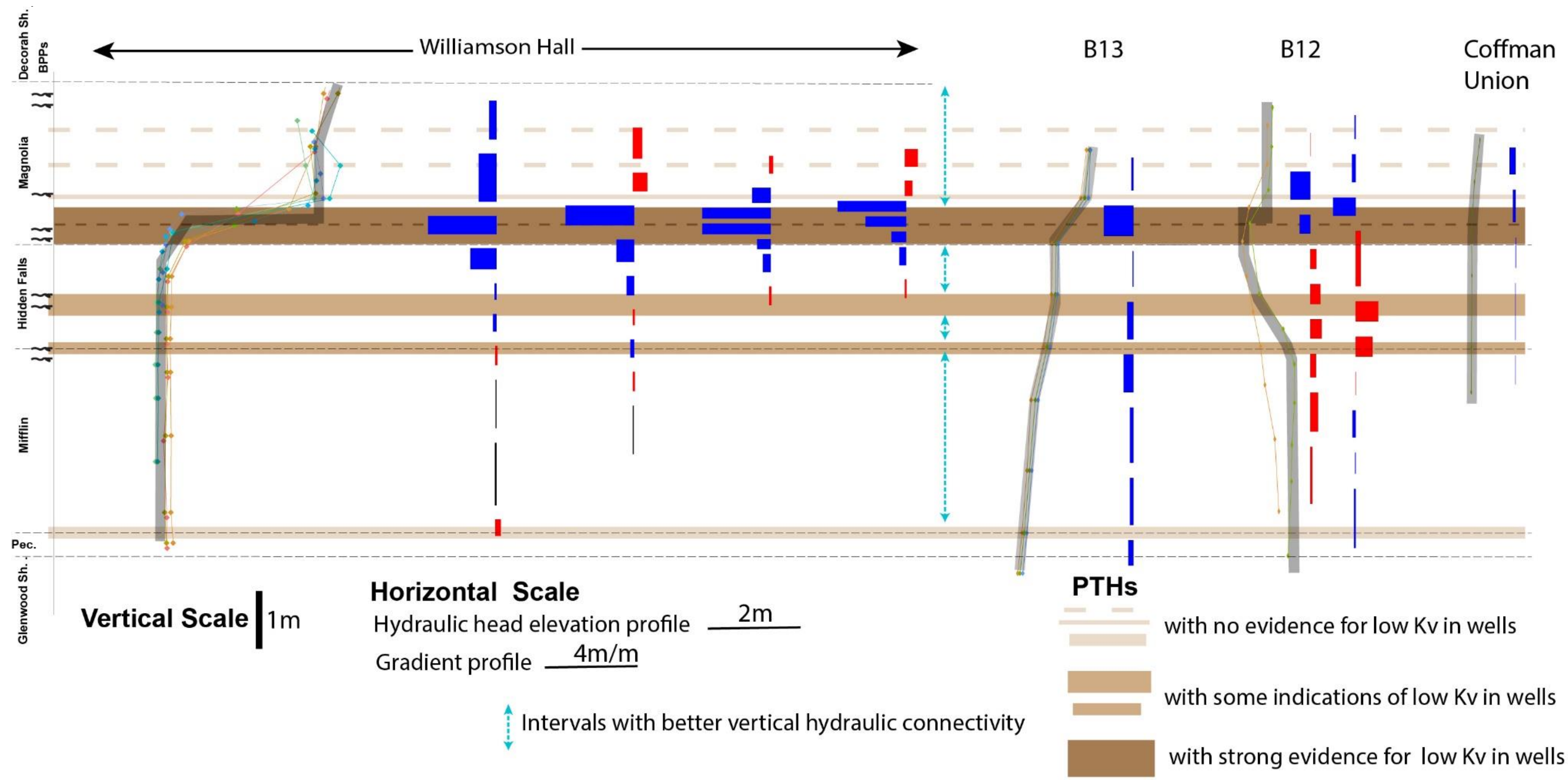

A
AC Equiv. Piezometric Head (m)
245.25
245.00
244.75
244.50
244.25
244.00
243.75
243.50
243.25
03/06/2019
04/06/2019
05/06/2019
06/06/2019
07/06/2019
08/06/2019
09/06/2019
10/06/2019
11/06/2019
12/06/2019
13/06/2019
14/06/2019
15/06/2019
Date/Time
Interval Top Depth (mbgs)
1 8.02
2 8.85 Magnolia
3 9.64
4 10.52 Hidden Falls
5 11.43
6 12.35 Mifflin
7 13.57
8 14.65
Pecatonica
9 15.35 Glenwood
B
1
2
3&4
5&6
upper Mifflin to Glenwood
7,8,9
C
temperature (C)
11.5
11
10.5
8
9
7
6
5
4
3
lowermost Magnolia to Glenwood
2
1
upper to middle Magnolia

Fig. 28



Williamson Hall
B13
B12
Coffman
Union
Decorah Sh.
BPPs
Magnolia
Hidden Falls
Mifflin
Pec.
Glenwood Sh.
Vertical Scale
1m
Horizontal Scale
Hydraulic head elevation profile
2m
Gradient profile
4m/m
Intervals with better vertical hydraulic connectivity
PTHs
with no evidence for low Kv in wells
with some indications of low Kv in wells
with strong evidence for low Kv in wells

Fig. 29

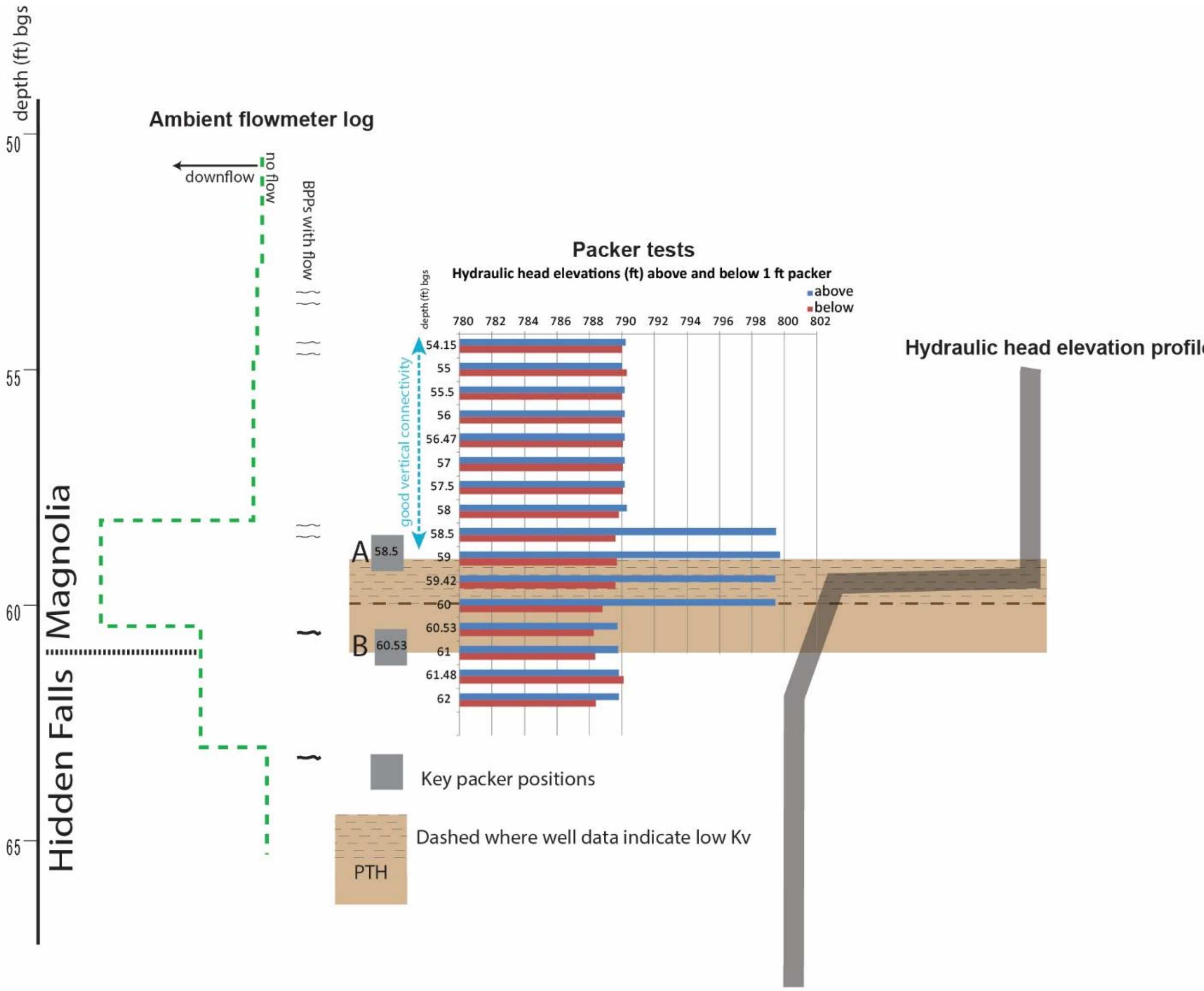

depth (ft) bgs
50
55
60
65
Magnolia
Hidden Falls
Ambient flowmeter log
downflow
no flow
BPPs with flow
Packer tests
Hydraulic head elevations (ft) above and below 1 ft packer
above
below
780 782 784 786 788 790 792 794 796 798 800 802
54.15
55
55.5
56
56.47
57
57.5
58
58.5
59
59.42
60
60.53
61
61.48
62
good vertical connectivity
A
58.5
B
60.53
Hydraulic head elevation profile
Key packer positions
Dashed where well data indicate low Kv
PTH

Fig. 30

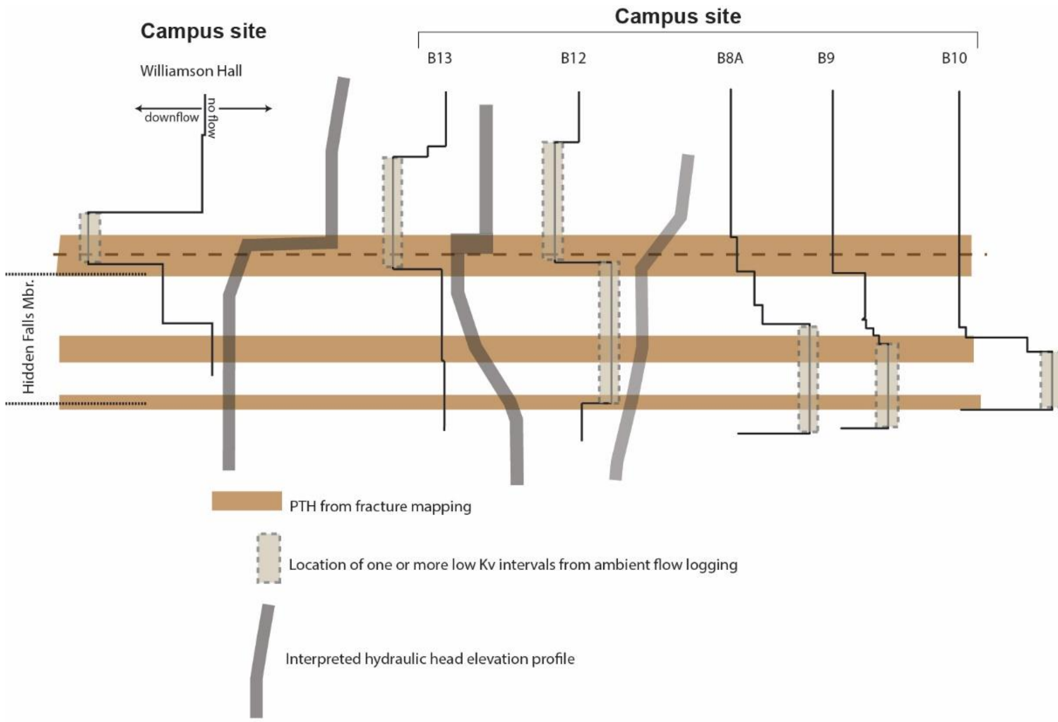

Campus site
Williamson Hall
downflow
no flow
Campus site
B13
B12
B8A
B9
B10
Hidden Falls Mbr.
PTH from fracture mapping
Location of one or more low Kv intervals from ambient flow logging
Interpreted hydraulic head elevation profile

Fig. 31

REFERENCES

Anderson, J.R., Runkel, A.C., Tipping, R.G., Barr, K., D.L., and Alexander, E.C., Jr., 2011, Hydrostratigraphy of a fractured, urban, aquitard: in Miller, J.D., Jr., Hudak, G.J., Tittkop, C., and McLaughlin, P.I., eds, Archean to Anthropocene: Field Guides to the Geology of the Mid-Continent of North America: Geological Society of America Field Guide 24, p. 457-475.

Alexander, E.C., Jr., Alexander, S.C., and K.D. Barr, 2001, Dye tracing to Camp Coldwater Spring, Minneapolis, MN: MGWA Newsletter, v. 20, no. 4, p. 4-6.

Alexander. E.C., Jr. 2016, Water Quality in Bore Holes at the 2016 MCES Regulator 04 Site.

Barr Engineering, 1983, Site characterization study and remedial action plan, General Mills solvent disposal site, June, 1983: On file at the Minnesota Pollution Control Agency. Inc.,

August, 1987: On fi le at the Minnesota Pollution Control Agency.Bradbury, K.R., Gotkowitz, M.B., Hart, D.J., Eaton, T.T., Cherry, J.A., Parker, B.L., and Borchardt, M.A., 2006, Contaminant transport through aquitards: Technical guidance for aquitard assessment: American Water Works Research Foundation Publication, 142 p.

Cooke ML, Simo JA, Underwood CA, Rijken P (2006) Mechanical stratigraphic controls on fracture patterns within carbonates and implications for groundwater flow. Sed Geol 184(3–4): 225–239

Eaton TT, Anderson MP, Bradbury KR (2007) Fracture Control of Ground Water Flow and Water Chemistry in a Rock Aquitard. Groundwater 45(5):601-615

Ferguson HF (1967) Valley stress release in the Allegheny plateau. Bull Int Assoc Eng Geo 4(1):63‑71.

Gross MR, Engelder T (1991) A case for neotectonic joints along the Niagara escarpment. Tectonics 10(3):631‑641.

Kanivetsky, R., 1978, Hydrogeologic map of Minnesota: Bedrock Hydrogeology. Minnesota Geological Survey Map Series, S-2.

Meyer JR, Parker BL, Cherry JA (2008) Detailed hydraulic head profiles as essential data for defining hydrogeologic units in layered fractured sedimentary rock. Environ Geol 56:27–44.

Meyer JR, Parker BL, Cherry JA (2014) Characteristics of high resolution hydraulic head profiles and vertical gradients in fractured sedimentary rocks. J Hydrol 517:493-507

Meyer JR, Parker BL, Arnaud E, Runkel AC (2016) Combining high resolution vertical gradients and sequence stratigraphy to delineate hydrogeologic units for a contaminated sedimentary rock aquifer system. J Hydrol 534:505-523

Molnar, P. (2004), Interactions among topographically induced elastic stress, static fatigue, and valley incision, J. Geophys. Res., 109.

Mossler, J.H., 1972. Paleozoic structure and stratigraphy of the Twin Cities Region. In: Sims, P.K., Morey, G.B. (eds.), Geology of Minnesota, A Centennial Volume. Publication of the Minnesota Geological Survey, pp. 485-497.

Mossler, J.H., 1985, Sedimentology of the Middle Ordovician Platteville Formation, southeastern Minnesota: Minnesota Geological Survey Report of Investigations 33, 27 p.

Mossler, J.H., 2008, Paleozoic stratigraphic nomenclature for Minnesota: Minnesota Geological Survey Report of Investigations 65, 76 p., 1 pl.

Nichols, T.C., Jr., 1980, Rebound, its nature and effect on engineering works: Quarterly Journal of Engineering Geology, London, v. 13, p.133-152.

Pehme, P.E., B.L. Parker, S.W. Chapman, and J.A. Cherry, 2014. Temporary Sensor Deployments: a Method for Improved Insight into Hydraulic Variations and Design of Permanent Multilevel Installations. Proceedings of International Discrete Fracture Network Engineering Conference, Vancouver, Canada. Paper #239.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Green, J.A., 2003, Hydrogeology of the Paleozoic bedrock in southeastern Minnesota: Minnesota Geological Survey Report of Investigations 61, 105 p., 2 pls.

Runkel AC, Steenberg JR, Tipping RG, Retzler AJ (2013) Geologic controls on groundwater and surface water flow in southeastern Minnesota and its impact on nitrate concentrations in streams. Minnesota Geological Survey Open File Report 14-2, 70 pp plus appendices and figures

Runkel, A.C., Tipping, R.G., Green, J.A., Jones, P.M., Meyer, J.R., Parker, B.L., Steenberg, J.A., and Retzler, A.J., 2014 Hydrogeologic Properties of the St. Lawrence Aquitard, Southeastern Minnesota, Minnesota Geological Survey OFR 14-04, 119p.

Runkel et al. (2015 Runkel, A.C., Steenberg, J.R., Tipping, R.G, Janzen, S., and Retzler, A., 2015 Hydraulic conductivity and hydrostratigraphy of the Platteville Formation, Twin Cities Metropolitan Area, Minnesota: Minnesota Geological Survey OFR 15-01, 28p, Appendices.

Runkel, A.C., Tipping, R.G., Meyer, J.R., Steenberg, J.R., Retzler, A.J., Parker, B.L., Green, J.A., Barry, J.D., Jones, P.M., 2018, A multidisciplinary-based conceptual model of a fractured sedimentary bedrock aquitard: improved prediction of aquitard integrity. Hydrogeology Journal, https://doi.org/10.1007/s10040-018-1794-2

Terzaghi RD (1965) Sources of error in joint surveys. Géotechnique 15(3):287–304

Underwood CA, Cooke ML, Simo JA, Muldoon MA (2003) Stratigraphic controls on vertical fracture patterns in Silurian dolomite, northeastern Wisconsin. AAPG Bull 87(1):121–142

Wyrick GG, Borchers JW (1981) Hydrologic effects of stress-relief fracturing in an Appalachian valley. US Geol Surv Water Suppl Pap 2177, 51 pp